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FRICTIONAL PROPERTIES OF CEDAR CITY QUARTZ DIORITE

H. R. Pratt A. D. Black

F. J. Bonney

Terra Tek, Inc.

TECHNICAL REPORT NO. AFWL-TR-72-122

December 1972

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This report was prepared by Terra Tek, Inc., Salt Lake City, Utah, under Contract F29601-71-C-0099. The research was performed under Program Element 62701B, Project 1515, and was funded by the Advanced Research Project Agency (ARPA) under ARPA Order No. 1515.

Inclusive dates of research were May 1971 through June 1972. The report was submitted 10 November 1972 by the Air Force Weapons Laboratory Project Officer, Captain Stoney P. Chisolm (DEV-F).

This technical report has been reviewed and is approved.

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Captain, USAF
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ABSTRACT

(Distribution Limitation Statement B)

A field and laboratory program was conducted to determine the frictional and deformational properties of Cedar City quartz diorite. In-situ tests on joint surfaces ranging in area from 22 to 795 square inches indicate a decrease in initial and residual shear strengths with increasing area. Laboratory data should be scaled appropriately depending on joint size, wave length and amplitude as compared to in-situ joints. Strength and modulus of jointed and unjointed specimens are similar until shearing begins when the strength of joint samples decreases. Field tests on specimens with single and multiple joints oriented at different angles to the axial stress indicate a significant geometric effect and that unfavorably oriented joints determine the shear strength of the entire joint block until that joint interacts with adjacent blocks. Servo-controlled direct shear laboratory tests on natural and artificially prepared joints over a normal stress range of 60 to 1500 psi indicate that there is a geometric effect with roughness but that this may be overridden by a contact area and/or asperity strength effect present in natural joints. This gives rise to lower friction angle than in smoother but perfectly mated artificial surfaces. Initial and residual coefficients of friction are a function of both normal stress and displacement. Dilation of both natural and artificial joints occurred during shearing at lower normal stress (<300 psi) but the joints compressed at higher normal loads. Dilation that occurred in field tests was related to the wave length and amplitude of the joint. Stick slip phenomena was noted in some of the laboratory tests at high normal stresses but not at low stresses or in any of the in-situ tests.

CONTENTS

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

SECTION I

INTRODUCTION

The purpose of this program was to measure the deformation and frictional properties of jointed rock specimens in the field and to relate these properties to corresponding laboratory properties. Among the in-situ specimens joint surface area and joint orientations ranged widely. Relationships developed as a result of this field and laboratory program will be used in the analysis of ground motion data from high explosive simulation tests performed by the Air Force Weapons Laboratory. A secondary objective of this program was the development of more portable equipment for preparation of the in-situ specimens.

Data collected from previous high-explosive experiments have demonstrated that joints, and other discontinuities control the failure mode and deformation characteristics of in-situ rock masses. Material property data for the tests were primarily derived from extensive laboratory tests on intact rock and not from in-situ jointed specimens. Extrapolation of laboratory data to define properties of the in-situ rock mass may not be valid depending on the characteristics of the joints and other structural features.

Frictional properties of rocks or modeling material simulating rocks have been studied extensively in the laboratory under a variety of loading conditions. Patton (Ref. 1) conducted direct shear tests on rock and modeling material with various surface geometries and modified the classic Coulomb-Navier friction equation $\tau = c + \sigma_n \tan\phi$ to take account for the geometric component of the asperities (i). He also indicates there are multiple modes of failure during the shearing process. Coulson (Ref. 2) conducted direct shear tests on several rock types over a range of surface roughnesses. He noted a decrease in initial coefficient of friction with increasing normal pressure and indicated that brittle fracture is the chief mode of failure of

the asperities. Four types of shear strength-displacement curves were defined. Other direct shear studies include Hoskins and others (Ref. 3) using a double shear apparatus, Hoek (Ref. 4) on large specimens of a wide range of rock types, and Wallace and others (Ref. 5) on amphibolite from the Auburn damsite area. In addition, Rengers (Ref. 6) has analyzed the influence of joint roughness on frictional properties.

Jaeger (Ref. 7) conducted triaxial tests on single and multiply jointed andesite specimens up to 6 inches in diameter and to confining pressures of 6000 psi. Byerlee (Refs. 8 and 9) conducted triaxial tests on granite at high confining pressures (up to 87 ksi) and found a decrease in the coefficient of friction with displacement on fractured and virgin surfaces but an increase then a decrease on finely ground surfaces. He noted that stick slip is the prevailing phenomenon during sliding. Triaxial tests on sandstone with artificial joints with various surface roughnesses have been performed by Logan (Ref. 10).

In comparison to the extensive laboratory data there are few studies of frictional properties of in-situ rock masses. Extensive testing was conducted by Wallace and others (Ref. 5) in the amphibolite at the Auburn damsite, Haverland and Slebir (Ref. 11) in a granite at Grand Coulee, Washington, Krasmanovic (Ref. 12) in limestone, and by Evdokimov and Sapegin (Ref. 13) on a jointed granite specimen several feet square. Kimishima and others (Ref. 14) conducted a biaxial shear test in a jointed limestone mass.

SECTION II

SITE SELECTION AND ROCK TYPE

The site chosen for the in-situ test was located at the Three Peaks area about 14 miles northwest of Cedar City, Utah, in a massive altered quartz diorite (tonalite) intrusive (Fig. 1). The site is about two miles north of the site at which a series of in-situ tests was conducted in a previous program (Ref. 15). Joint spacing at the surface ranged from 1 to 8 feet. The surface of the rock was unweathered, and the area over which individual tests were conducted was reasonably level (Fig. 2). The rock is composed of plagioclase feldspar, amphibole, biotite, clay minerals, and magnetite. Thin section analysis shows that the highly fractured plagioclase phenocrysts are enclosed in a groundmass of fine grained plagioclase, quartz, biotite, magnetite and clay minerals which are also fractured (Fig. 3). Because of the highly fractured nature of the rock and the ubiquitous nature of the clay minerals, the rock has an unusual porous texture not typical of hard igneous rock. Preliminary laboratory tests indicated that the rock had a much lower compressive strength compared to other crystalline rocks such as Westerly granite.

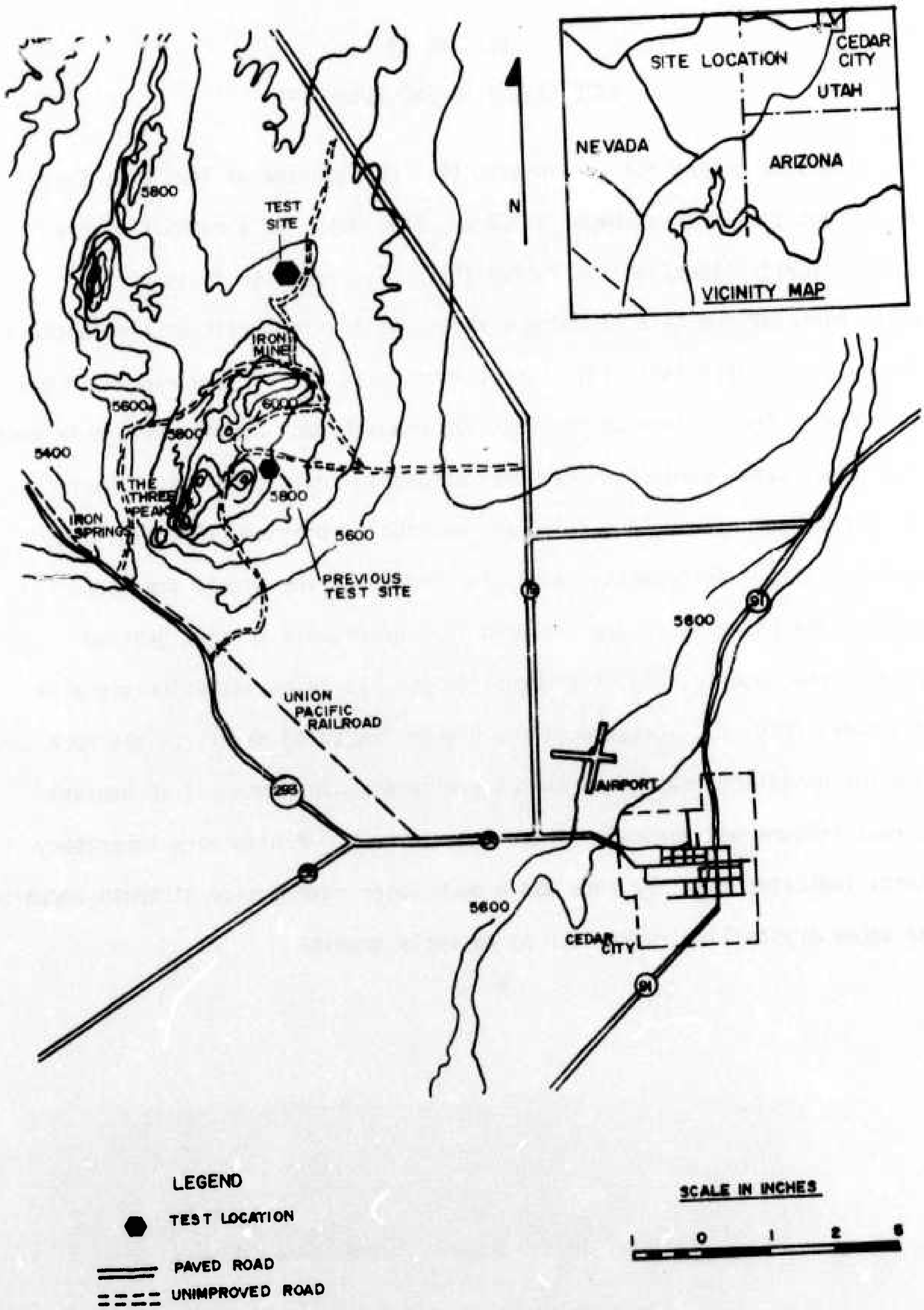


Figure 1. Test site location, Cedar City, Utah.

Figure 2. General area of in-situ tests. Note several tests and cores along a single joint.

Figure 3. Photomicrograph of Cedar City quartz diorite illustrating altered texture. (x36)

SECTION III

TEST PROGRAM

Field Program

The program at Cedar City, Utah, consisted of 17 in-situ tests (Table I) on jointed specimens of quartz diorite having the configuration of an equilateral triangular prism of constant cross sectional area (Fig. 4). All the in-situ tests and the joint samples cored for laboratory testing are located within a small area (Fig. 5). Tests 1-4 were conducted on specimens 4.5 feet or greater in length each having a single natural joint oriented at a different angle for each test. The angles ranged from 30-75° to the axis of loading. After conducting these tests it was decided to conduct two additional smaller tests, 17 and 18, at 37½° and 52½°, respectively. These tests were conducted to determine the effect of joint orientation on frictional properties. For each test, the orientation of the joint specifies the geometric components of shear and normal stress.

Several tests (2,5,6,7,8,9) ranging in size from 6x12 inch to 3.0x6.0 feet, each having a single joint oriented at 45° to the axis of loading, were tested to ascertain the effect of joint surface area on frictional properties. The surface area ranged from 22 to 795 square inches.

Tests 10-14 were conducted on samples 3.0x6.0 feet or greater having multiple joints. For example, test 10 had multiple intersecting joints (Fig. 6) and test 12 had two parallel joints oriented at 45° to the axis of loading (Fig. 7); one with calcite and one without a calcite filling. Test 14 (Fig. 8) was conducted to study uniformity of strain and end effects. Test 15 (Fig. 9) was conducted at a test site near Park City, Utah, on a sloping surface. The tests were conducted on 2.0x3.0 foot specimens of Nugget sandstone to prove the performance of the portable drill rig developed

Table I

Test Series On Jointed Rock

Test No.	Size	Angle of Load to Joint Axis	Comment
1	3.0x7.0 ft.	30°	Single joint
2	3.0x4.5 ft.	45°	Single joint
3	3.0x4.5 ft.	60°	Single joint
4	3.0x4.5 ft.	75°	Single joint
5	6x12 in.	45°	Single joint
6	8x12 in.	45°	Single joint
7	9x18 in.	45°	Single joint
8	12x18 in.	45°	Single joint
9	2.0x3.0 ft.	45°	Single joint
10	3.0x6.0 ft.	multiple intersecting	Multiple joints
11	3.0x6.0 ft.	3 @ 30-45°	Multiple joints
12	3.0x6.0 ft.	2 @ 45°	Multiple joints
13	3.0x6.0 ft.	1 @ 45°; 1 @ high ∆	Multiple joints
14	2.0x3.0 ft.	N/A	Unjoint sample to study end effects
15	2.0x3.0 ft.	N/A	Size will be at least 2.0x3.0 ft. with angle of sloping surface greater than 30°
16	2.0x3.0 ft.	Not conducted	
17	12x24 in.	37½°	Single joint
18	12x18 in.	52½°	Single joint
19	12x18 in.	60°	Single joint (repeat of 3)

Figure 4. Specimen configuration, test 1, 3.0x7.0 foot sample with 30° joint.

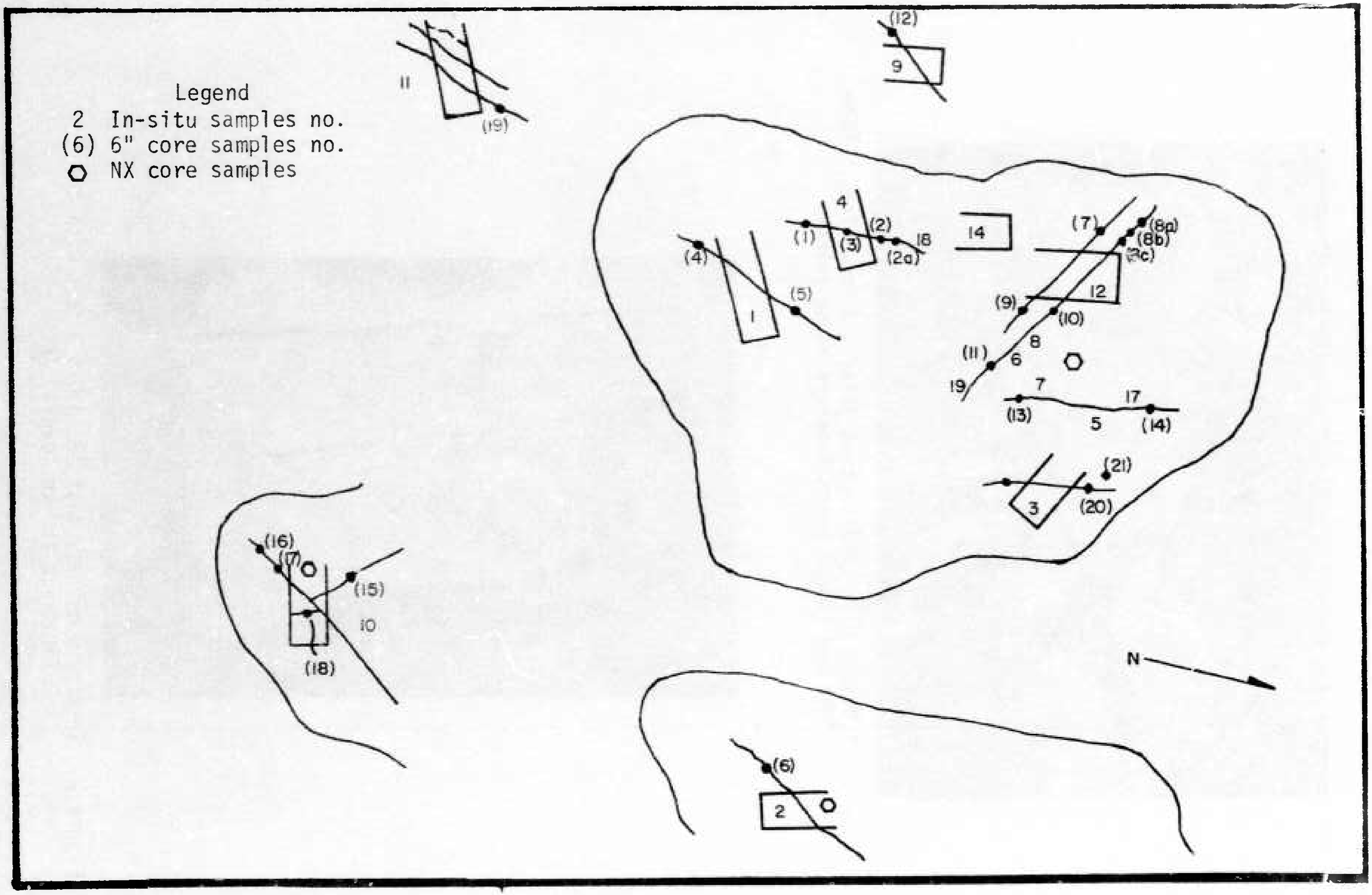


Figure 5. Sketch map of location of in-situ specimens and cores taken along joints.

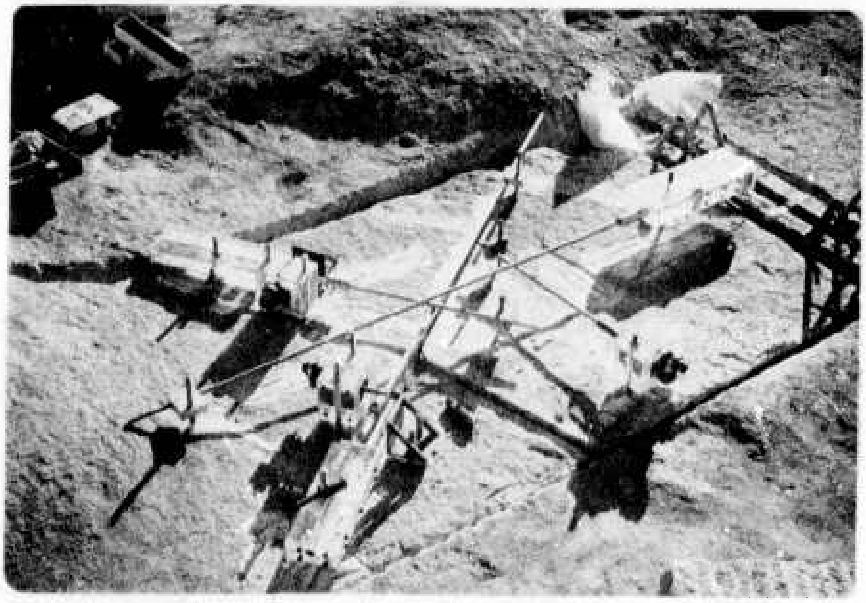


Figure 6. Specimen with intersecting joints, 3.0x6.0 feet. Note DCDTs and linear potentiometers along joints.

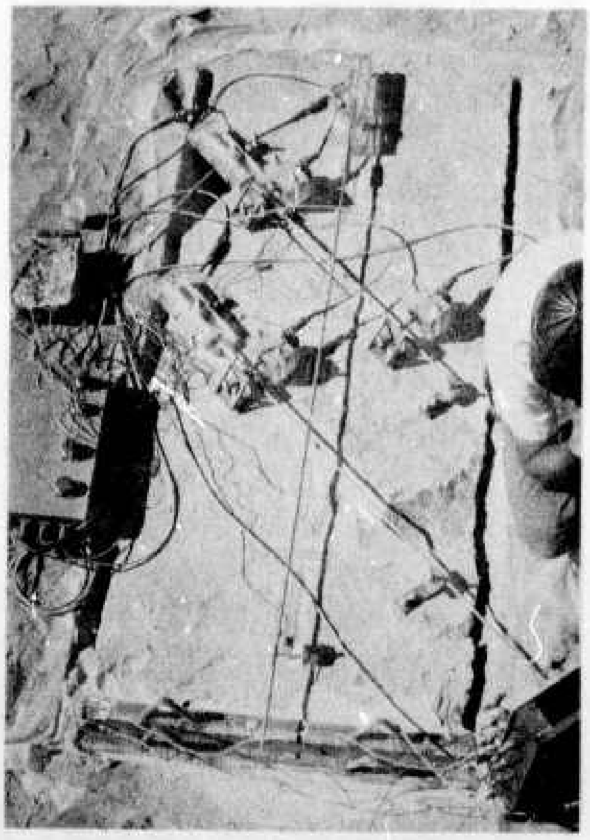


Figure 7. In-situ specimen, test 12, 3.0x6.0 feet with two joints at 45° to loading axis.

Figure 8. In-situ unjointed specimen, test 14, 2.0x3.0 feet, used to analyze end effects and uniformity of strain.

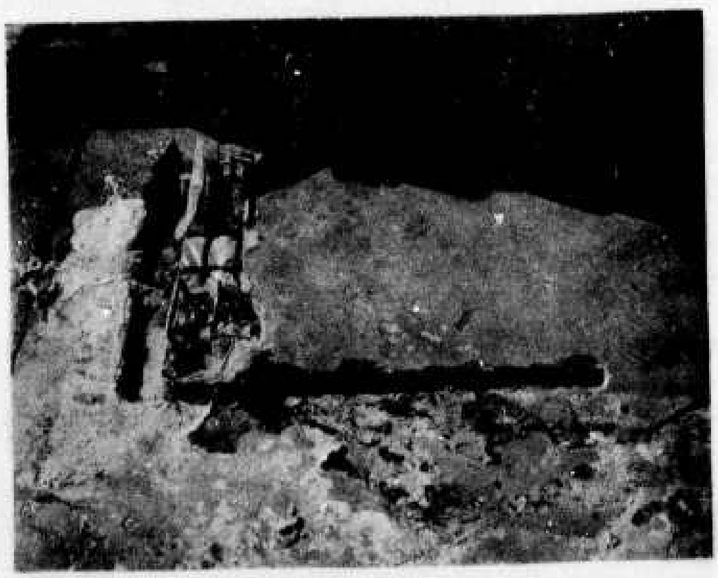


Figure 9. In-situ specimen, test 15, in sandstone near Park City, Utah.

during this program. Test 19 was a rerun of test 3 to test the reproducibility of our observations for a specimen with a single joint oriented at 60°.

Laboratory Program

Direct shear tests were conducted on 6-inch cores containing natural undisturbed joints (Fig. 10) and solid NX cores, which were subsequently sawed or broken in a Brazilian tension test to provide two other controlled surface roughnesses. NX cores were also tested in uniaxial stress to define a stress-strain behavior for the quartz diorite. A total of 46 direct shear and uniaxial stress tests were performed.

The jointed specimens were tested in a 235-kip servo-controlled direct shear machine over a range of normal stress from 60 to 1521 psi. The purposes of the direct shear tests were to study the

(1) Shear stress observed in the laboratory under the same normal stress conditions, σ_n, observed in the field tests.

(2) Effect of normal stress on shear stress and coefficient of friction. This is coupled with joint profiling to compare initial joint configuration and subsequent modification with magnitude of shear and normal stresses.

(3) Effect of prior history of loading on surface modification. Tests are conducted at a given normal stress on both virgin surfaces or surfaces that have already been tested at lower normal stresses.

(4) Effect of normal load variability on frictional properties during uncontrolled and servo-controlled test conditions.

(5) Effect of surface roughness and of initial contact area on the frictional properties.

(6) The variability of frictional properties along a single joint.

(7) Vertical displacement as a function of the normal stress.

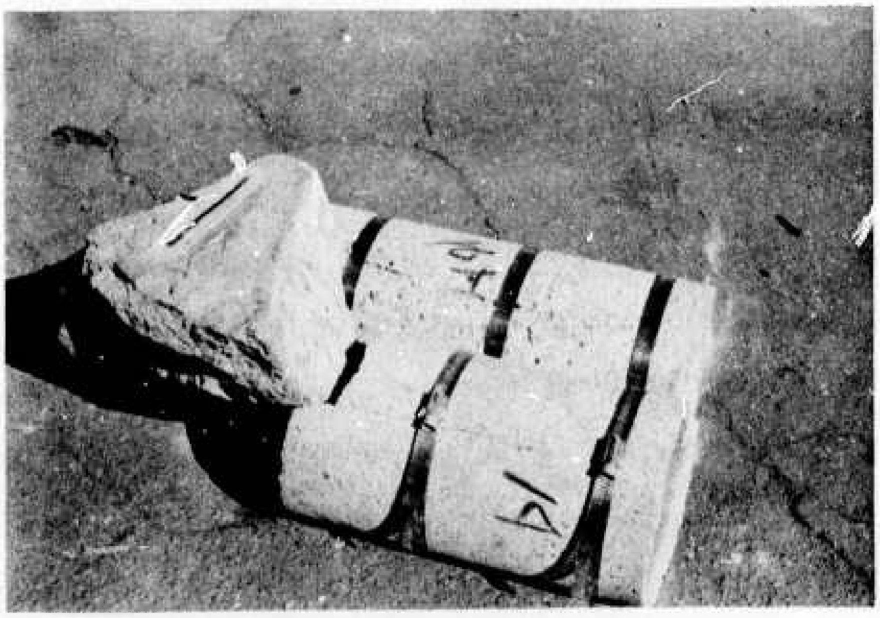


Figure 10. Typical 6-inch cores with undisturbed joints. Also calcite coated joint surface on failed in-situ specimen (6x12 in.).

SECTION IV

EXPERIMENTAL TECHNIQUES

Specimen Preparation

The in-situ specimens were prepared by the drilling technique and equipment developed on a previous program (Ref. 15). Briefly, three slots, two at 60° to the surface of the rock to form the sides of the specimen and one vertical slot to form the end of the specimen are cut by a drilling technique (Fig. 11). In this technique a row of 1½-inch diameter holes are drilled on 2½-inch centers. The web between the holes is subsequently removed by a drill situated between drill guides. Jointed specimens are prepared by cutting a single 60° slot, backfilling with sand, then cutting a 6-inch wide vertical slot to accommodate the flat jack package. After the flat jack package is grouted in place, and the hydrostone grout allowed to harden, the final slot is cut in a manner similar to the first. Specimens 12x18 inches and smaller were prepared using a template bolted to the surface of the rock. The template accommodates a 3/4-inch carbide drill with holes spaced 1/2-inch apart. The webs between the holes are subsequently broached using a power impact chisel drill. The surface of the specimen is prepared for strain gaging by grinding the surface smooth, filling holes and pits with epoxy, and regrinding and sanding to attain a final smooth surface. The joint was then profiled on the top surface by recording the trace of both sides of the joint on acetate strips. A new portable drill rig (Fig. 12) was fabricated to prepare specimens on sloping surfaces and in more remote areas inaccessible to our present rig. The procedure for preparing the specimens is the same as with the present rig.

The laboratory specimens were cored along the same joints as were tested in-situ (Fig. 13). Prior to breaking the core from the host rock, the

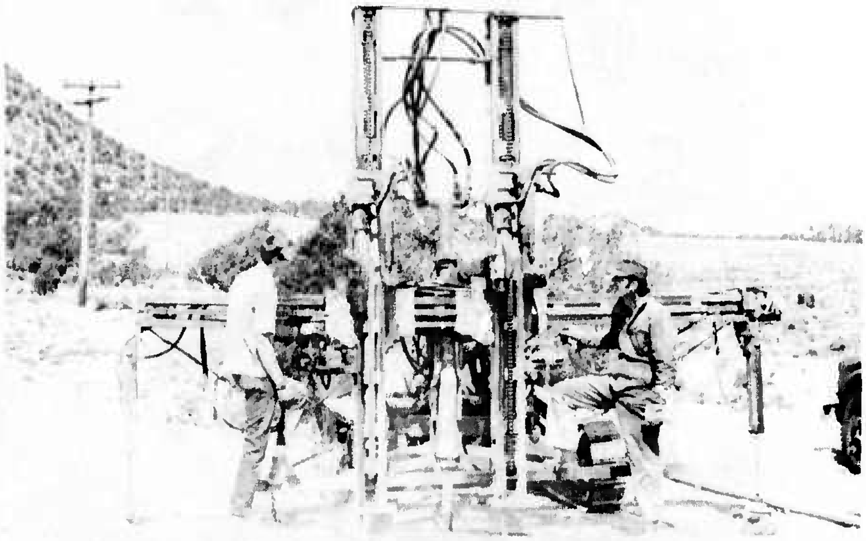


Figure 11. D-illing rig in vertical position at Cedar City, Utah

Figure 12. Portable drill rig at Park City, Utah.

Figure 13. Coring rig used to excavate jointed specimens adjacent to in-situ speci~en. Note core sample beyond rig.

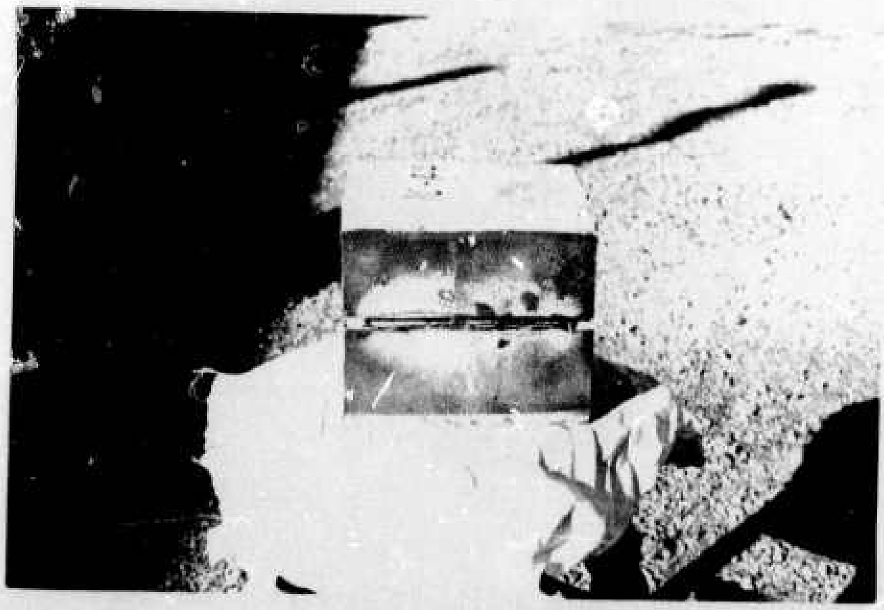


Figure 14. Cast hydrostone blocks containing 6x6-inch joint samples.

specimens were banded so that no movement would occur along the joint. Each 6-inch diameter core was approximately 15-18 inches long and provided two adjacent 6x6-inch samples containing a natural joint. During all cutting procedures in the laboratory the joint was sealed so that water could not penetrate along the joint thus changing its character. Solid NX core was taken at several locations. These cores were either (1) cut in half lengthwise by a diamond saw providing a direct shear specimen with a surface relief of about 600-700 microinches, (2) broken in a Brazilian tension test to provide a fresh surface with a relief of about 0.1-0.2 inch, or (3) prepared by grinding the end and strain gaging for testing in uniaxial stress. For (1) or (2), the specimens were then cast in hydrostone prior to testing in direct shear (Fig. 14). On virgin samples (not profiled) the bands were broken just prior to shearing.

Loading System

The system used to apply the axial load to the in-situ system consisted of a flat jack package pressurized by a hydraulic system. The package consisted of three triangular stainless steel flat jacks sandwiched between two triangular 2-inch steel plates. Details of the flat jack construction and the method of calibration of efficiency as a function of pressure and size is described in Ref. 15. The pneumatic-hydraulic pumping system was fabricated to supply water containing water soluble oil to prevent rusting of the flat jacks in the loading package (Fig. 15). Pressure was supplied by 1100-psi and 6600-psi Sprague pumps and monitored by 10,000-psi Crosby Bourdon tube gages and 1000-, 5000-, and 10,000-psi pressure transducers.

Instrumentation

In-situ Tests: The pressure applied to the joint specimen was measured by 10,000, 5000 and 1000 psi transducers. DCDTs (Hewlett-Packard 7 DCDT 1000)

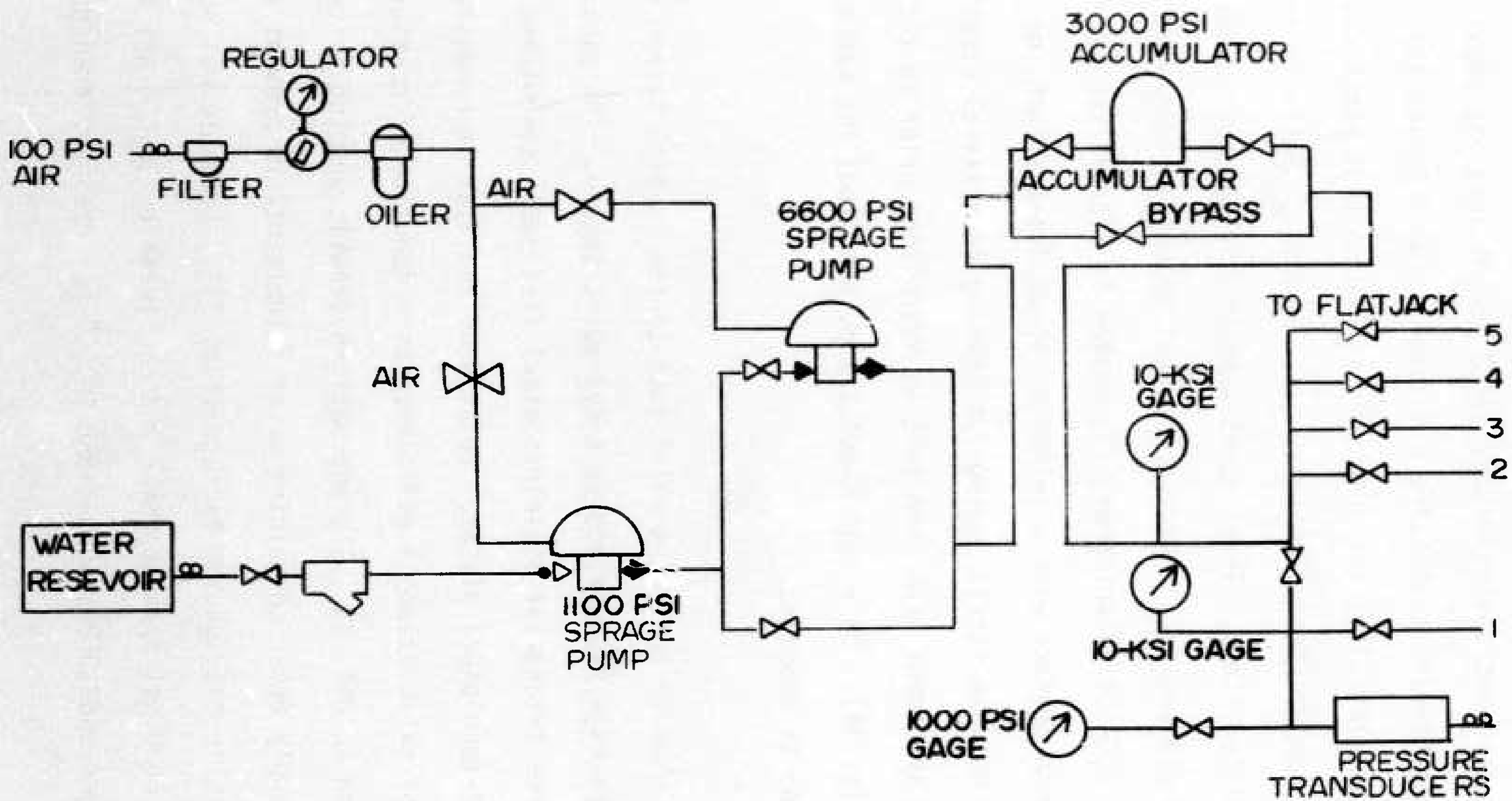


Figure 15. Pneumatic-hydraulic pumping system.

measured total axial strain and shear displacement along the joint on both the top and side of the specimen (Fig. 16). For multiply jointed specimens, shear displacement was monitored on more than one joint (Fig. 7). Displacement perpendicular to the direction of shear (i.e. opening and closing of the joint) (Fig. 17) was monitored by linear potentiometers (Markite 8120). Output from the pressure transducers, DCDTs, and linear potentiometers was monitored on a 9 channel oscillograph recorder (Bell and Howell No. 5-126) and an Esterline Angus X-Y recorder. BLH Model A-9 and A-9-4 Constantan Wire Grid paperback gages (2½ inches and 6 inches long) were placed axially and transversely at several locations on the top of the specimen. For test 14, strain gages were placed axially on both the top and sides of the specimen (Fig. 8). All gages are water proofed and temperature compensated. In addition, in test 14 a borehole deformation gage was used to monitor strain at three positions within the specimen.

Strain gage output was channeled through a 12 channel bridge balance (Terra Tek, Inc. Model 104A) to a 24 channel recorder (Esterline-Angus Multipoint Recorder No. E11245). A schematic of the instrumentation is shown in Fig. 18.

Laboratory Tests: The direct shear tests were conducted on a 235-kip servo-controlled direct shear machine (Figs. 19 and 20). Normal and shear stresses are applied by independently controlled 235-kip cylinders. This closed loop system makes it possible to keep the normal stress constant or vary it at will throughout the test (Fig. 21). Maximum shear displacement allowed is 3 inches but in most tests maximum displacement was 0.5-1.0 inch. Unique features of the test equipment include an oil bearing instead of roller bearings to reduce friction and an alignment scheme to prevent rotation during the test. Normal and shear stresses are monitored by calibrated load cells;

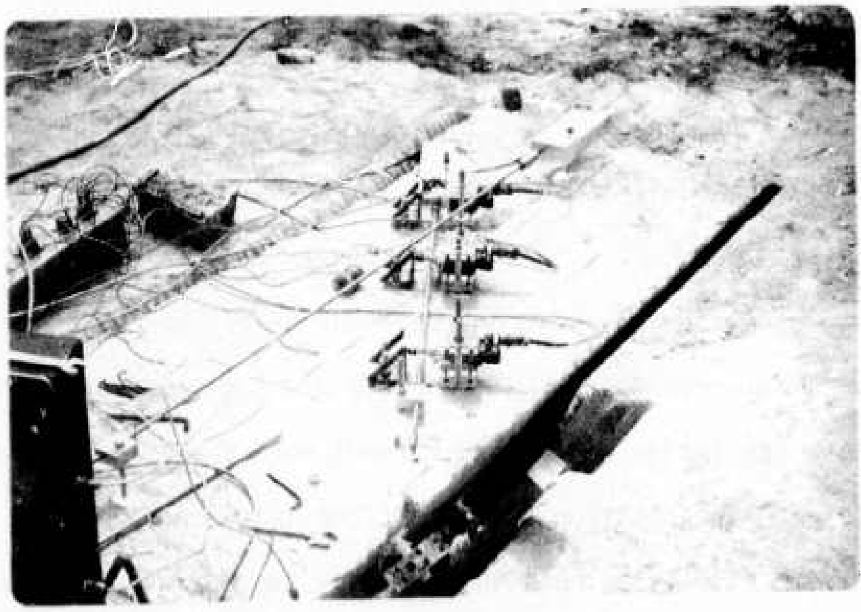


Figure 16. In-situ specimen, side view. DCDTs along joint on top and side surfaces and along axis of specimen.

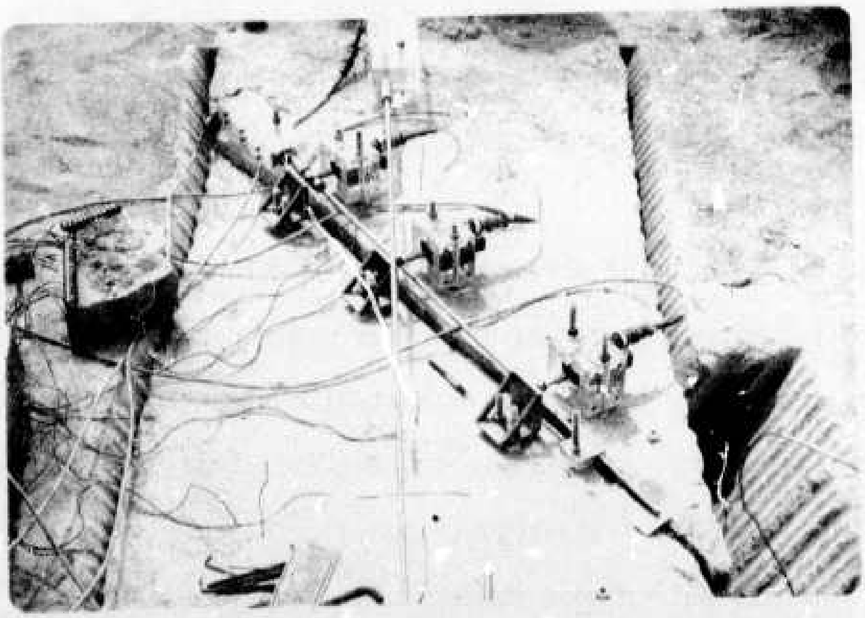


Figure 17. In-situ specimen. DCDTs along joint, three linear potentiometers across joint and several strain gages on top surface of the specimen. Note displacement of joint.

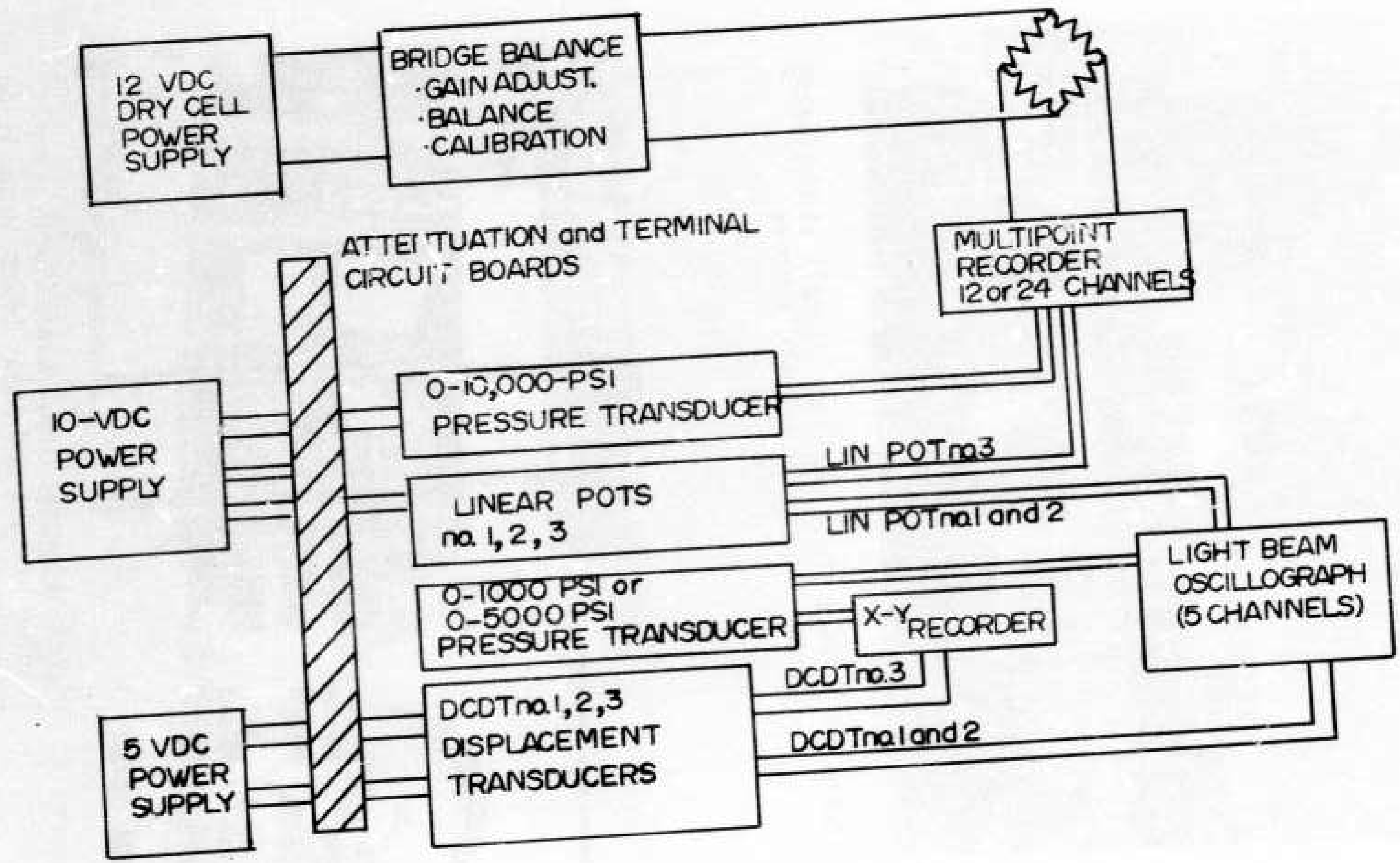


Figure 18. Schematic of instrumentation layout.

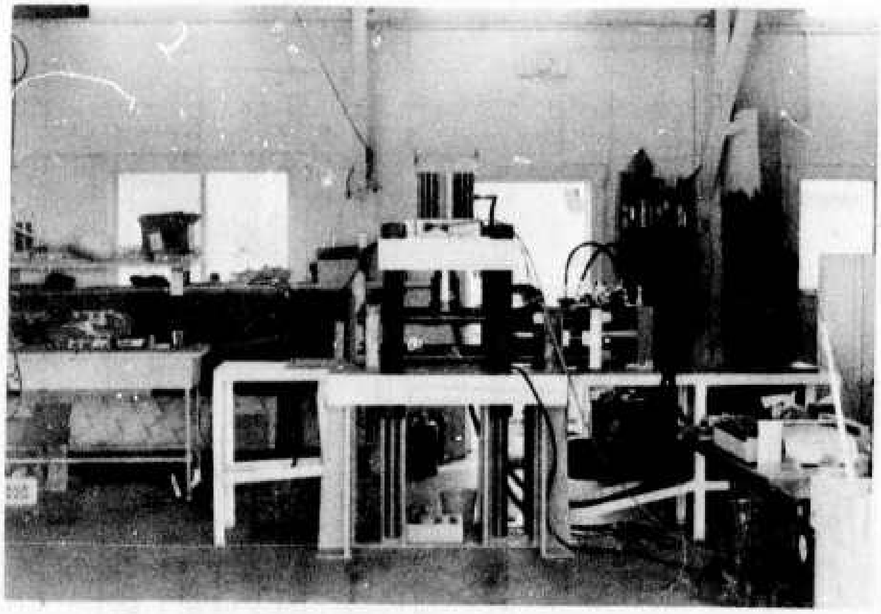


Figure 19. Direct shear machine, overall view showing shear and normal loading systems.

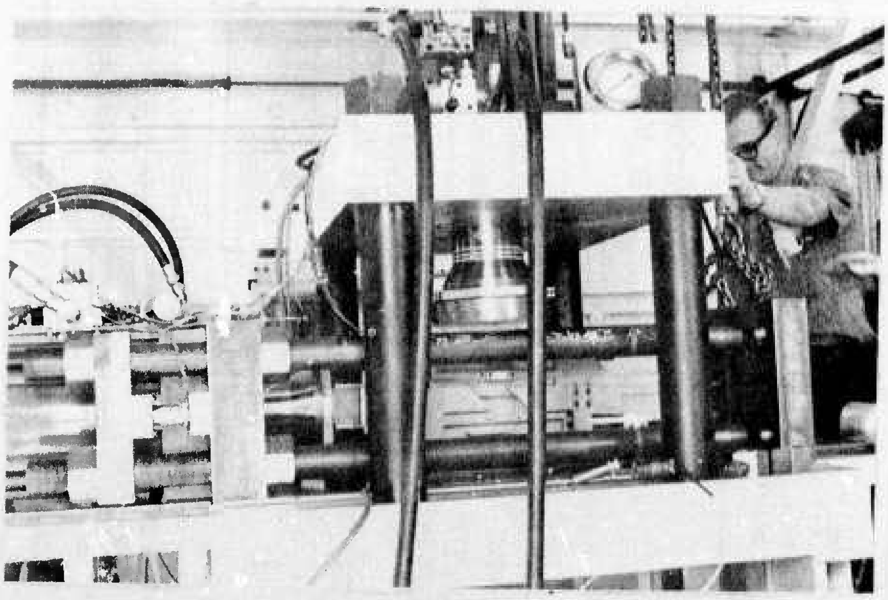


Figure 20. Direct shear machine. Close-up showing loading pistons and shear boxes in position to be tested.

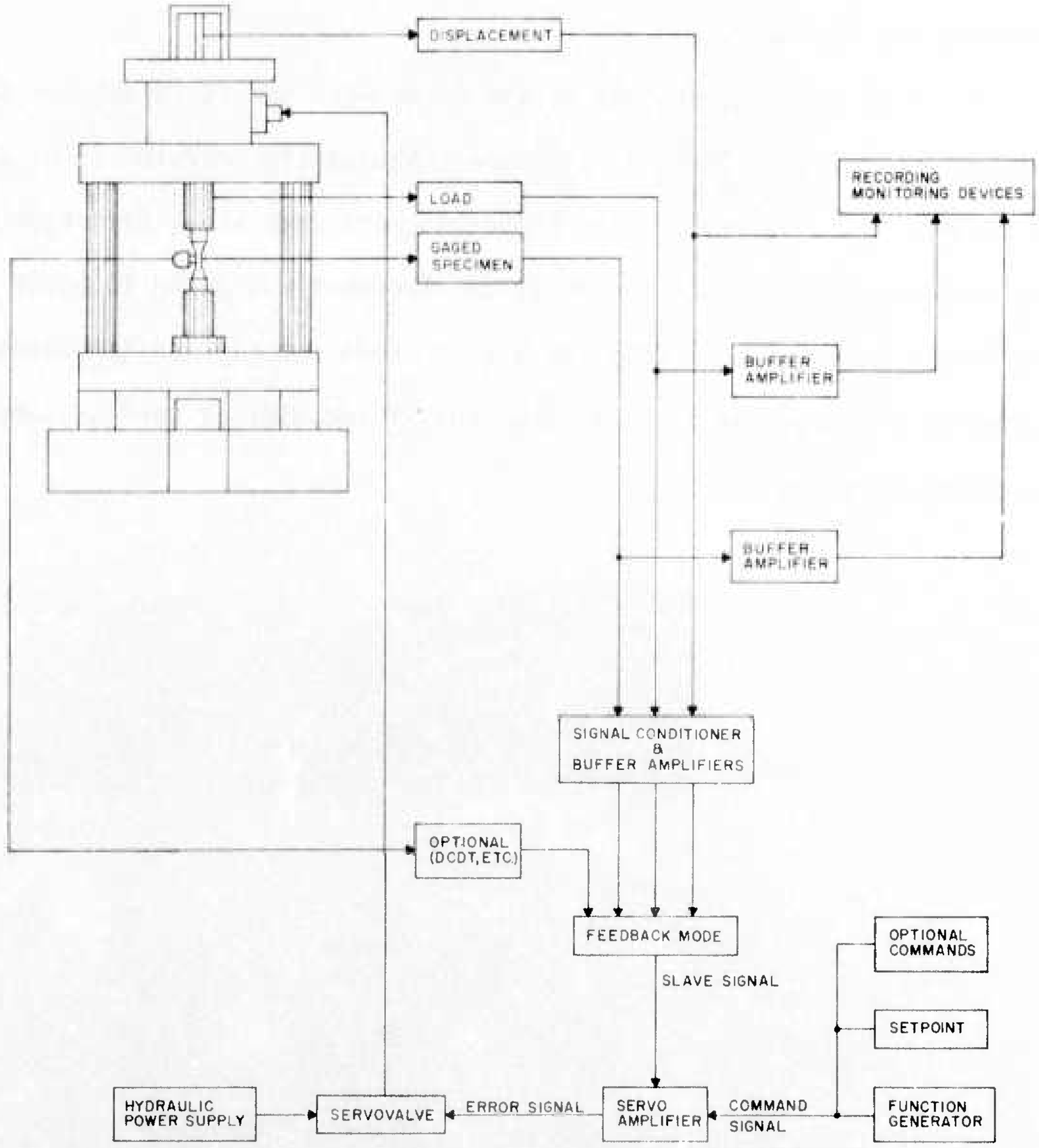


Figure 21. Schematic of closed loop servo system.

shear displacement by a single DCDT and the vertical displacement by two DCDTs, one mounted on either side of the shear box. Shear stress versus shear displacement is plotted on an X-Y recorder while shear displacement, normal stress, and displacement normal to the joint were plotted on an oscillograph recorder.

Prior to testing, several of the cores were pulled in tension to determine a joint "cohesion". These joints were subsequently profiled (Fig. 22) to an accuracy of .001 inch. Five traverses were made along each specimen in the direction along which the shear displacement was going to occur during the direct shear test. DCDTs are used to continuously monitor changes in relief as the traverse is plotted on an X-Y recorder at various sensitivities depending on relief.

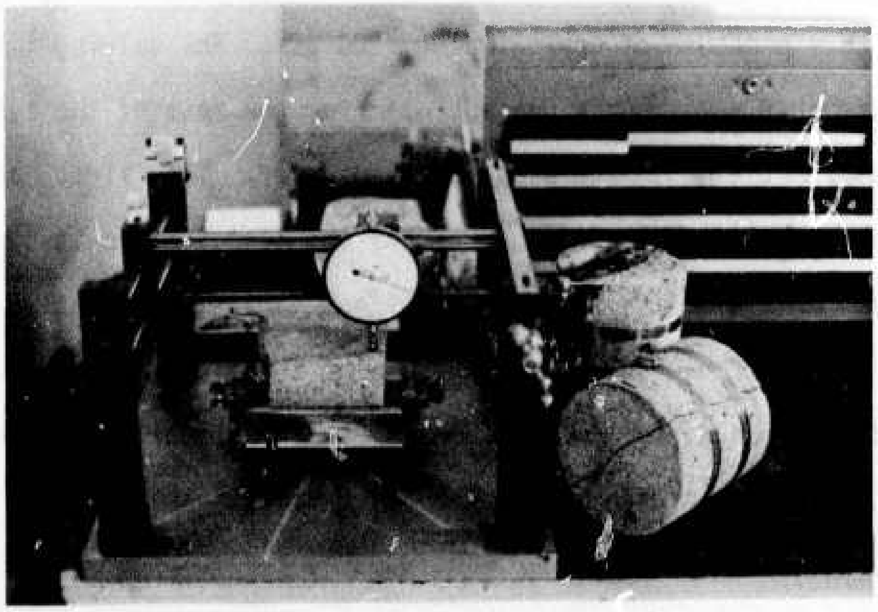


Figure 22. Joint profiler with 6-inch core ready for profiling. DCDTs are not attached.

SECTION V

TEST PROCEDURE

In-situ Deformation Tests On Jointed Rock

The first flat jack next to the specimen is pressurized to approximately 0.25-inch displacement (total width of three jacks is 0.5 inch), which corresponds to a pressure of approximately 200 psi. The valving is arranged so that the front flat jack can be shut off from the rest of the system except for a direct line to the pressure transducer. This first jack is then used as a pressure cell for the rest of the test. Since it contains a fixed volume of fluid, its thickness does not vary significantly, thus eliminating this test variable. The purpose of the first jack is to "snug up" the flat jack package. The specimen is usually slightly strained at this time. For tests in which the joint moved at less than 200 psi (e.g. test 1) the front jack was expanded continuously to 1.0 inch.

The second jack is then pressurized to a total width of 0.75 inch (0.58-inch displacement). If displacement along the joint or failure has not occurred before this displacement, the second jack is closed off and the third jack is pressurized to the same displacement. Displacement along the joint usually occurred during pressurization of this jack. Rate of loading was approximately 50 psi/minute. If failure of some type has not occurred at this point, then the valves to the second and third flat jacks are reopened and all the jacks except the front jack are pressurized simultaneously until failure of the rock or one of the flat jacks occurs. The first jack deflects only slightly after pressurization of the other jacks.

Laboratory Tests

In the laboratory direct shear tests, the predetermined normal stress

is applied by the vertical piston. Shear displacement rate is programmed and the shear stress, normal stress, shear displacements, and vertical displacements are monitored. For some tests the normal stress was allowed to vary at will during the test. For all tests the normal stress was compensated as the contact area between blocks change during displacement. A total change in area of 16% occurs when a 6x6-inch sample is displaced 1.0 inch. Rate of shear displacement was approximately 0.10 inch/minute. In tests where the surface was sheared at a series of normal stresses, the specimen was profiled before and after each test. The specimen was repositioned to the initial contact location prior to each test.

The unconfined compressive strength of NX cores with an L/D = 1.75 were determined at three different locations (Fig. 5).

SECTION VI

EXPERIMENTAL RESULTS

In-situ Tests

In-situ tests on prismatic specimens were conducted to determine the frictional properties of a representative rock mass and to correlate these results with frictional properties obtained from laboratory tests on the same natural joints. Seventeen in-situ tests were carried out (1) on specimens having single joints oriented at a variety of angles to the axis of loading, therefore having different components of shear and normal stress, (2) on specimens of different size in which the surface area of the joint ranged 22 to 795 in^2, (3) on specimens containing more than one joint, some parallel, some intersecting, and (4) on an unjointed specimen to determine uniformity of strain and end effects.

The average stresses acting on the natural joint in uniaxial stress are given by

$$\sigma_n = \frac{\sigma_a}{2} - \frac{\sigma_a}{2}\cos 2\alpha = \frac{\sigma_a}{2}(1-\cos 2\alpha) \qquad (1)$$

$$= \frac{p \cdot e}{2}(1-\cos 2\alpha)$$

$$\tau = \frac{\sigma_a}{2}\sin 2\alpha = \sigma_a \sin\alpha \cos\alpha \qquad (2)$$

$$= p \cdot e \sin\alpha \cos\alpha$$

during frictional sliding

$$\mu = \frac{\tau}{\sigma_n} \qquad (3)$$

where σ_n = normal stress acting on joint, σ_a = axial stress supplied by flat jack, p = pressure in flat jack, e = efficiency of flat jacks, τ = shear stress acting on joint at failure, μ = coefficient of friction. The initial shear strength (τ_i) is defined as the shear strength attained before a significant change in the slope of τ - displacement curve takes place. In some cases significant displacement, up to 0.1 inch, may occur before τ_i is reached. Residual shear strength (τ_r) is defined as the constant shear strength value reached after significant displacement has been reached. The test results are summarized in Table II.

Because, α, the angle between the σ_a and the joint is predetermined, the ratio of shear to normal stress is fixed for any given test. The magnitudes of the shear and normal stresses at failure for any test at a given angle will be a function of the joint properties such as roughness, size of sample, initial contact area, composition and amount of the joint filling, degree of alteration, mineralogy of rock and other factors.

Joint Orientation Effect: As was expected, the maximum shear stress increases as the angle α increased from 30° to 75°. Specimens with joints at 30°, 37½°, and 45° to axis of loading were able to withstand increased shear loads prior to appreciable movement along the joint (Fig. 23). The 37½° specimen exhibited a higher shear strength than expected because part of the joint "healed" and had to be sheared. A critical angle for the natural joint surfaces on the quartz diorite appears to be approximately 52° where a small amount of movement along the joint occurred prior to failure. At 60° and greater there was no movement along the joint prior to failure under uniaxial stress conditions; in fact, the 75° specimen exhibited measurable dilation. The critical angle is therefore slightly greater than 52°.

Effect of Surface Area: A series of tests was conducted on specimens of

Table II

Field Experiments

Expt.	Size	Joint Area in^2	α*	σ_{ax}**	τ_i	σ_n	μ_i	$Ex10^6$	Comments
1	3x7 ft.	1123	30	157	68	40	1.7	1.54	
17	12x18 in.	102	37½	545	263	202	1.3	.83	
2	3x4.5 ft.	795	45	543	272	272	1.0	.92	Poor data
9	2x3 ft.	353	45	771	386	386	1.0	.45	
5	6x12 in.	22	45	1900	950	950	1.0	1.72	
6	8x12 in.	39	45	1748	874	874	1.0	1.20	
7	10x18 in	61	45	322	161	161	1.0	1.00	
8	12x18 in.	88	45	752	376	376	1.0	.91	Calcite filled
12	3x6 ft.	795	45	337	169	169	1.0		
18	12x18 in.	78	52½	1266	673	808	.83	--	Not gaged
3	3x4.5 ft.	648	60	2362	1022	1772	.58	1.04	
19	12x18 in.	72	60	2028	878	1521	.58	.92	
4	3x4.5 ft.	581	75	2108	527	195	.27	.77	

*α in degrees

**σ_{ax}, τ, σ_n and E in psi

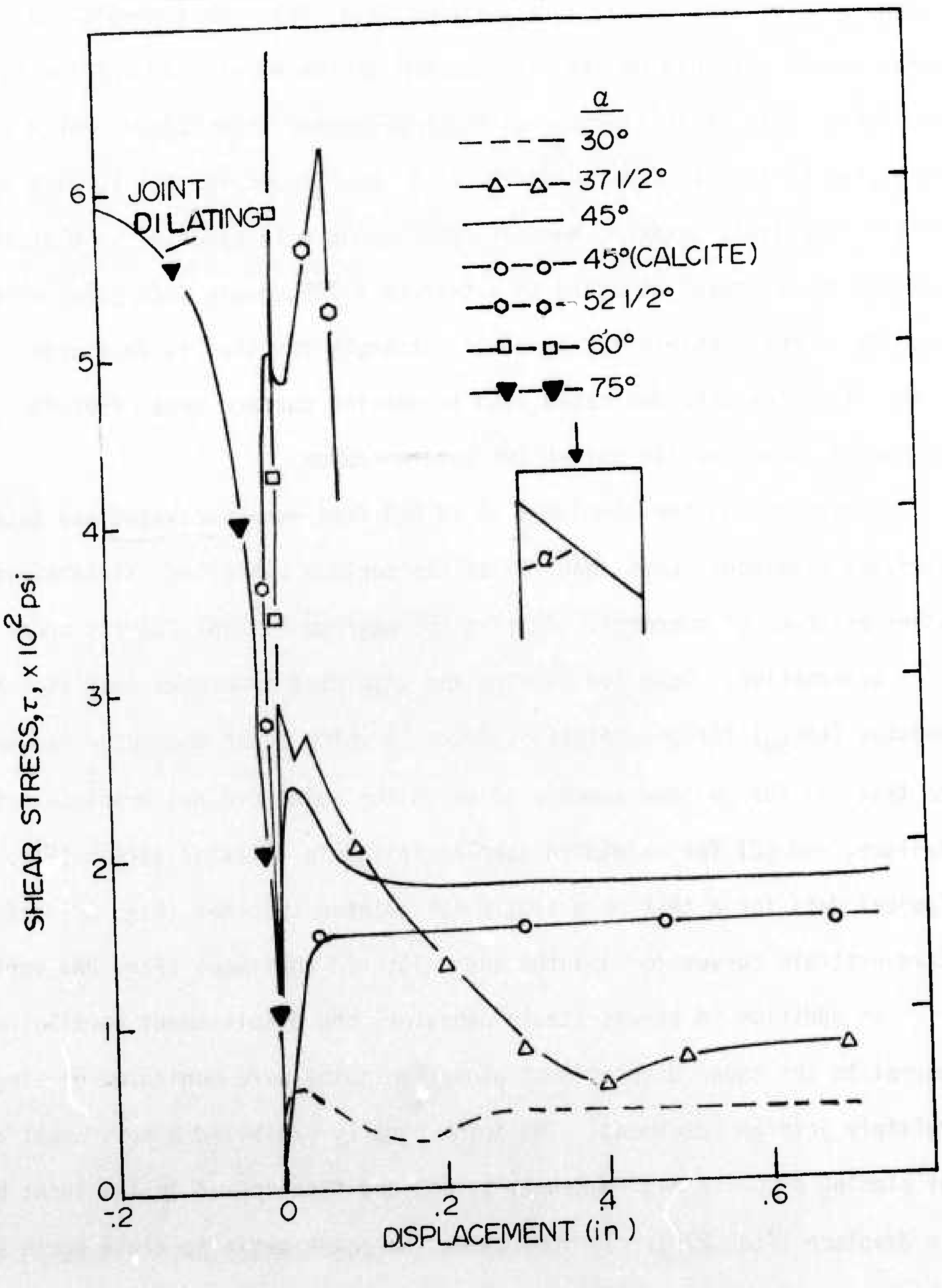


Figure 23. Shear stress versus displacement for specimens with single joint oriented at angles ranging from 30° to axis of loading.

different sizes each having a single 45° joint. The specimens ranged from 6x12 inches having a joint area of 22 square inches to a 3.0x4.5 foot specimen having a joint area of 795 square inches (Fig. 24). In general, the maximum shear stress attained during displacement decreased with increasing surface area (Fig. 25). Initial shear strength decreased from 950 psi for a 22 square inch area to 169 psi for one of the tests on 795 square inch surface area. This latter joint surface, however, was coated with calcite, so that the 272 psi maximum shear stress attained in a test on a 795 square inch joint without calcite is more representative of the strength for that surface area. Residual shear strengths also decreased with increasing surface area; from 450 psi at 22 square inches to 210 psi at 795 square inches.

After testing the specimens up to 2x3 feet were excavated and joint surfaces examined. Less than 15% of the surface exhibited slickensides or other evidence of movement. This is the maximum initial contact area.

Deformation: Data for jointed and unjointed specimens indicated that modulus ($\tan_{50}$) for the jointed samples in which shear did occur is similar to that (1) for jointed samples in which the joint did not displace prior to failure, and (2) for unjointed samples failed in uniaxial stress (Fig. 26). Typical data for a test on a single 45° jointed specimen (Fig. 27) and average strain-strain curves for jointed and unjointed specimens (Fig. 28) verify this.

In addition to stress-strain behavior, the displacement parallel and normal to the shear displacement along the joint were monitored on single and multiply jointed specimens. The joint usually exhibited a very small amount of closing prior to maximum shear stress and then opened as the joint began to displace (Fig. 27b). In some cases the joint began to close again as shearing progresses, undoubtedly this is related to the topography of the joint surface. This will be discussed in a later section.

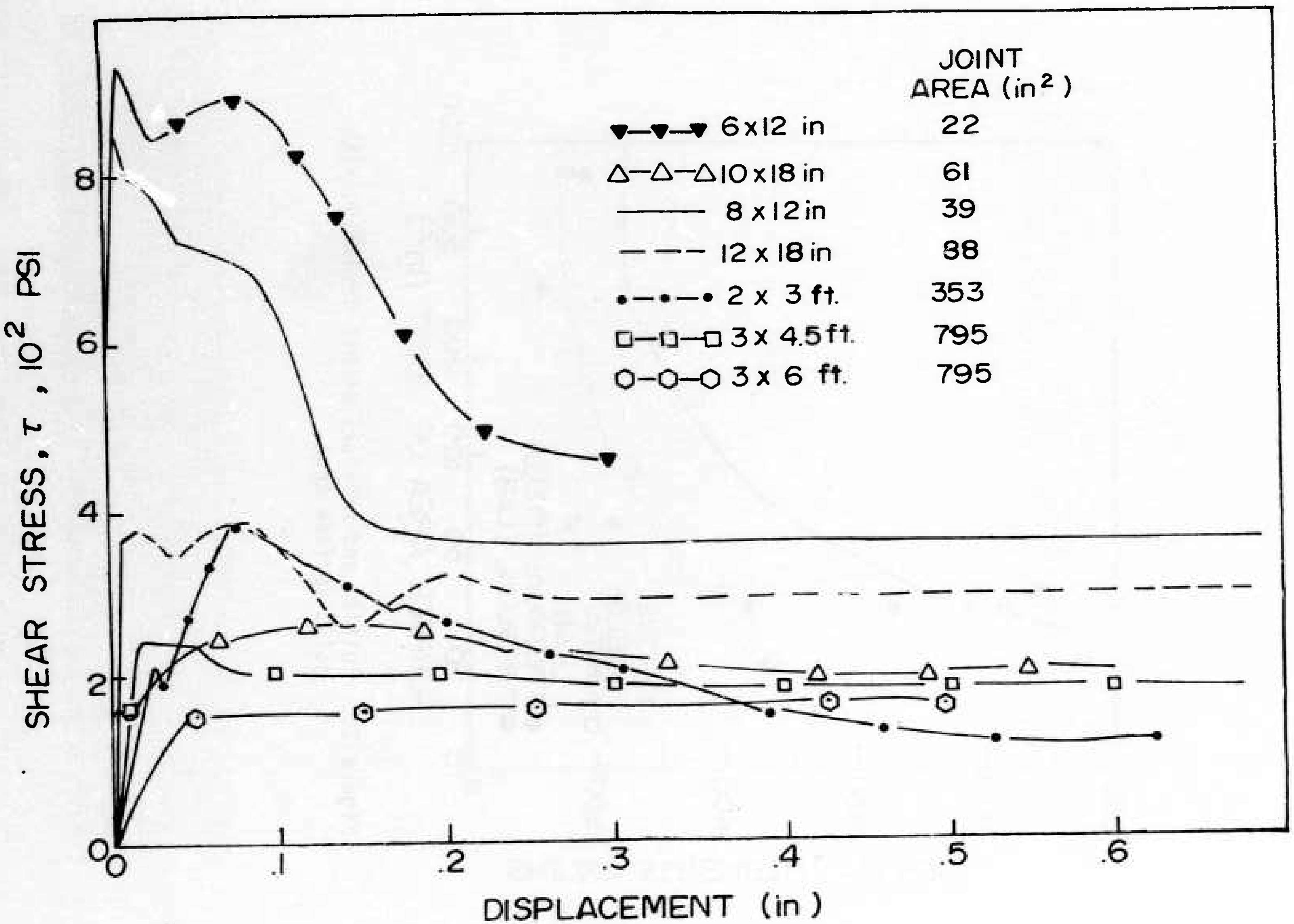


Figure 24. Shear stress versus displacement for joints with different surface areas. All specimens had a single joint oriented 45° to axis of loading.

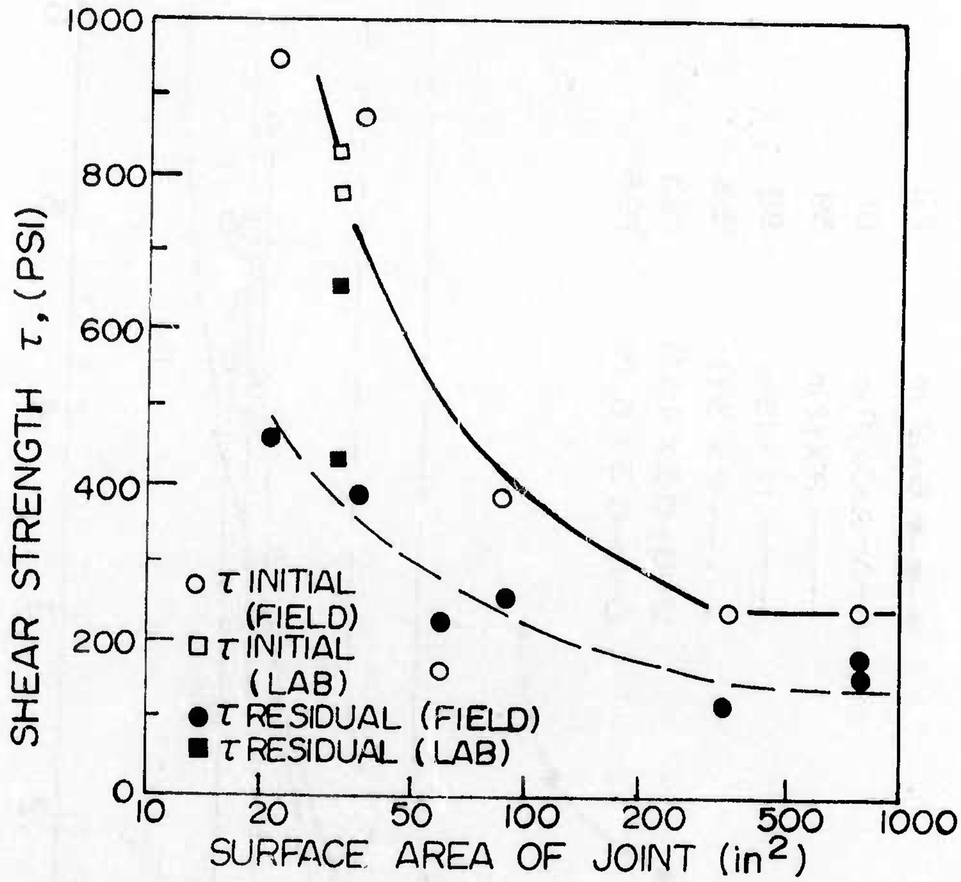


Figure 25. Initial and residual stress variation with joint surface area.

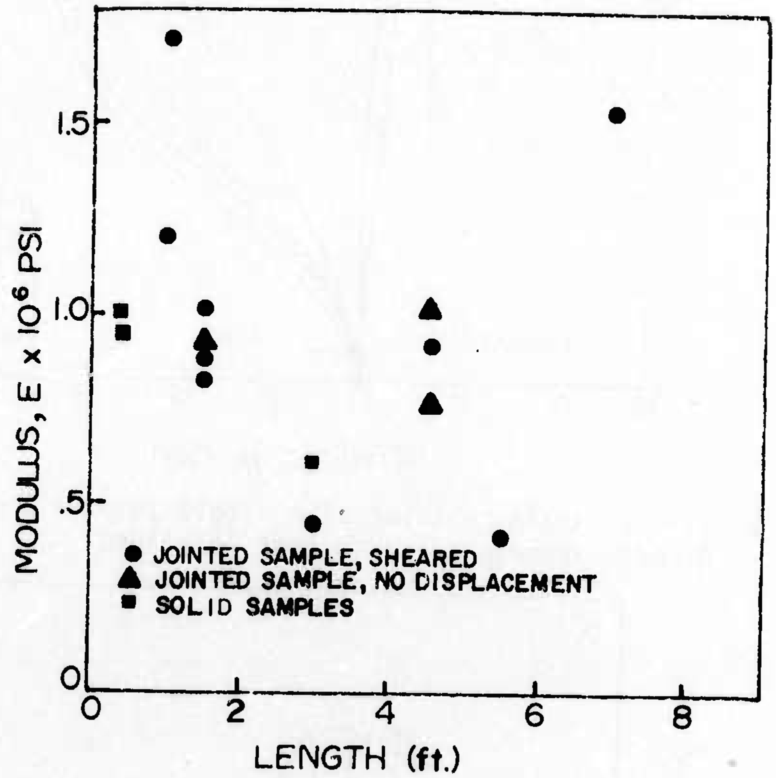
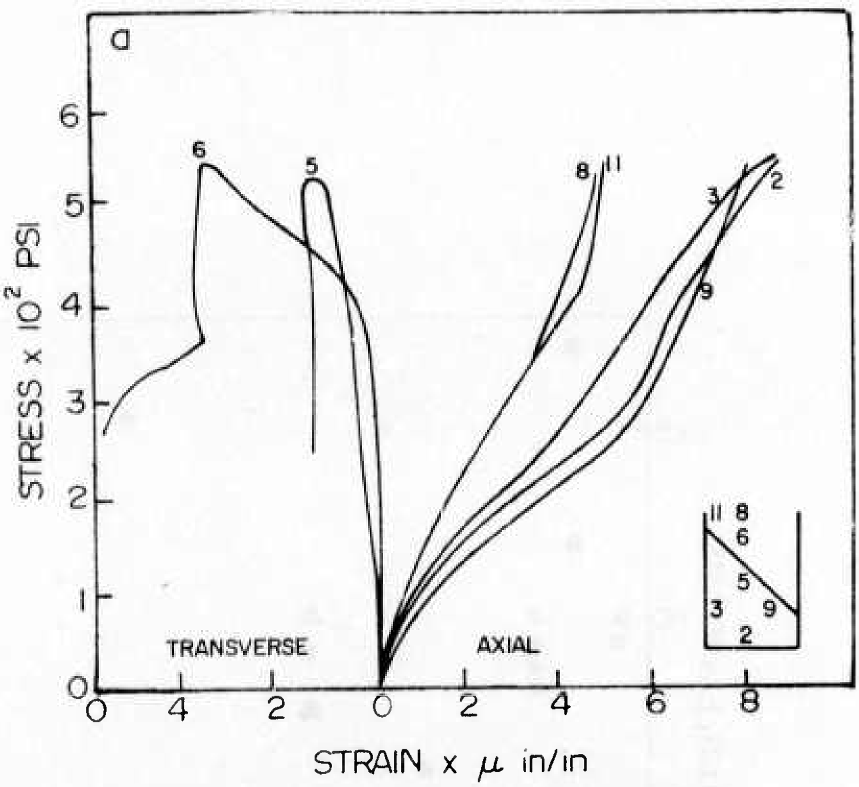
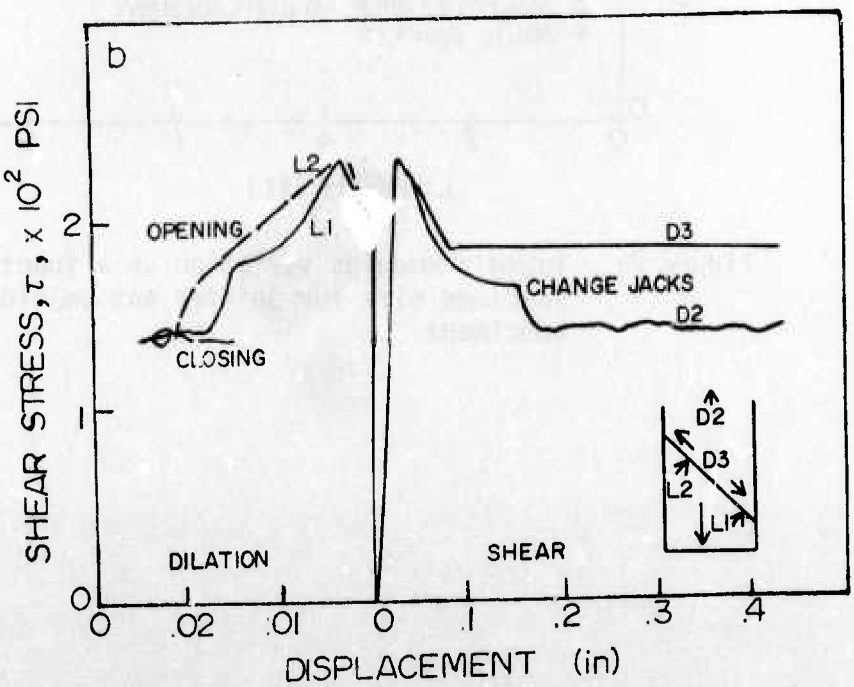


Figure 26. Young's modulus variation as a function of specimen size for jointed and unjointed specimens.



a. Stress-strain behavior of a single jointed specimen (45°). Numbers represent strain gage locations.



b. Shear stress-displacement behavior of a single joint specimen (45°). Ds are DCDT location and data and Ls are linear potentiometer location and data.

Figure 27. Stress-strain behavior of in-situ specimens.

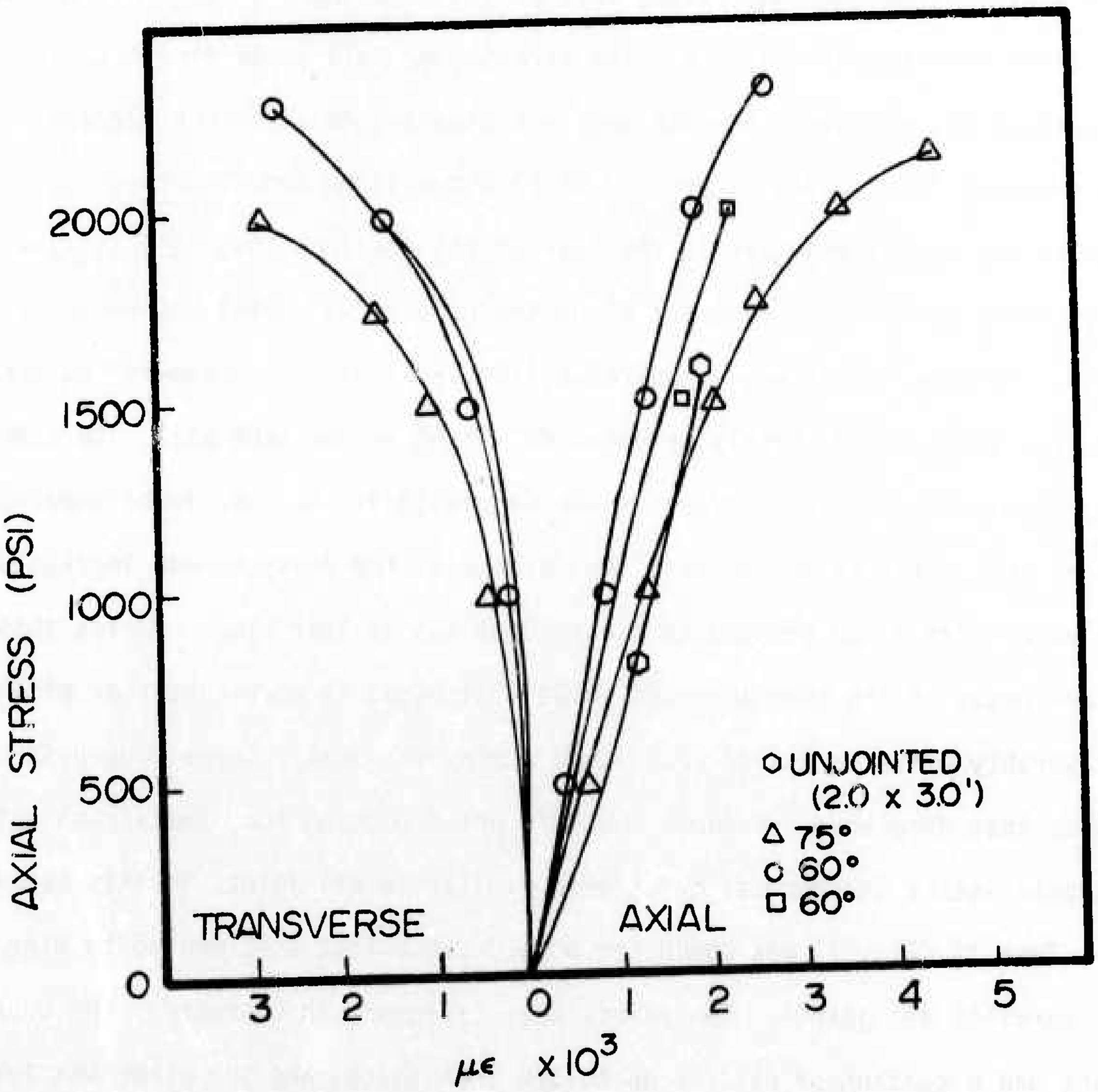
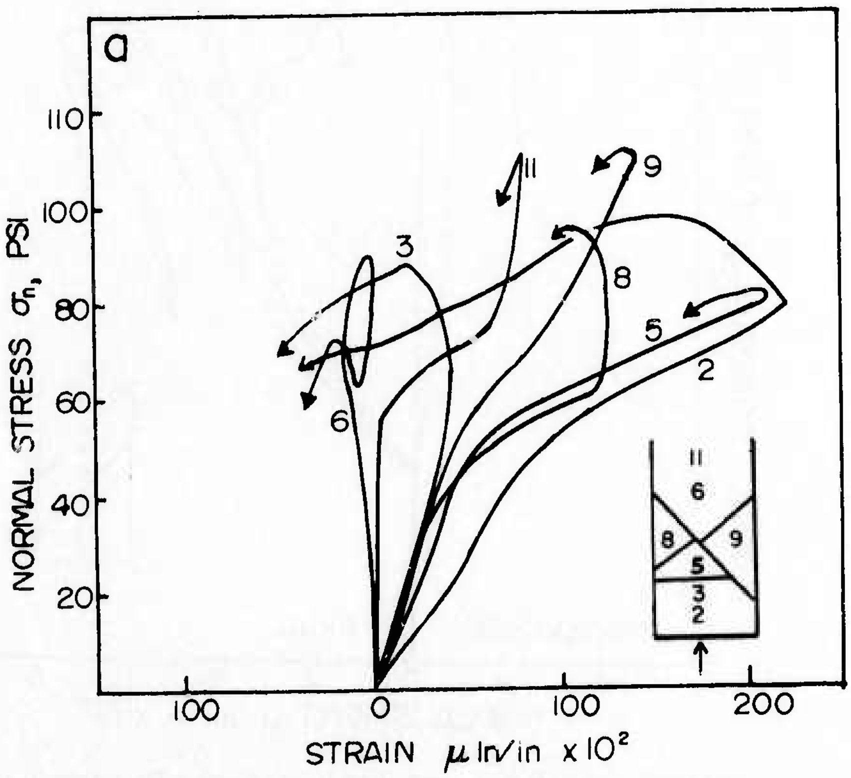


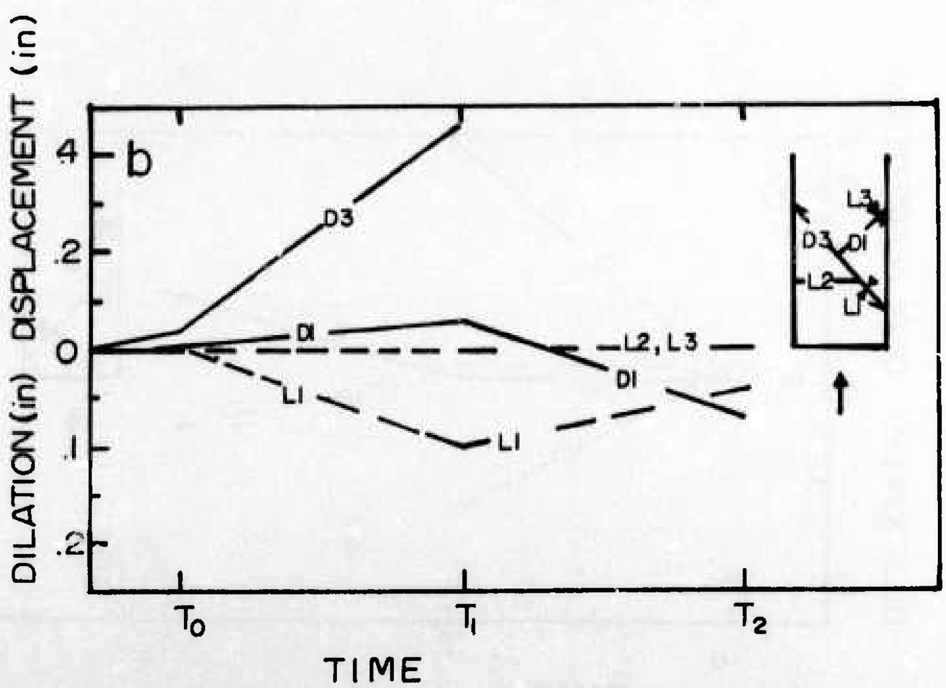
Figure 28. Stress-strain curves for samples with joints 60-75° to loading axis. Joints did not move.

Multiply Jointed Specimens: Four tests (10, 11, 12 and 13) were conducted on specimens containing more than one joint. Test 10 (Fig. 6) was conducted on a 3.0x6.0-foot specimen having sets of intersecting joints. Instrumentation locations are shown in Fig. 29. The strain gage data is difficult to interpret as various blocks within the specimen are strained to different degrees. The front of the specimen (gages 2 and 5) shows large amounts of strain immediately upon loading while the rear of the specimen (gage 11) is strained very little until after movement along the primary 45° joint has begun to occur. Maximum strain was exhibited by the front of the specimen. Movement occurred along the favorably oriented 45° joint at about 60 psi. The sample displaced about 0.5 inch before it was wedged (D3). As this joint sheared, it opened (L1) until it was wedged, then closed as the pressure was increased. The axial stress had dropped to about 30-35 psi at this time. During this second phase of the test a second joint (D1) began to move. Neither of the unfavorably oriented joints (L2) moved during the test. Cores from both joints that displaced and those that did not indicated that individual joint characteristics (roughness, etc.) were similar to all joints in this specimen.

Test 12 (Fig. 7) was conducted on a 3.0x6.0-foot specimen containing two parallel 45° joints. The joints were different in character, the back joint had a coating of calcite up to 1/8 inch thick, and the other was free of calcite and contained only limonite stain. This second joint was also "tighter" than the first. This is indicated by the closing of the rear joint (L1) prior to the opening after the joint began to move (Fig. 30b). The character of displacement curve (D1) is different from most curves in that the initial, maximum and residual stresses are the same. The front joint (D3) was displaced after the other had been displaced about 0.8 inch and subsequently wedged. The front joint opened as it was displaced (L3). As in the case of the specimen

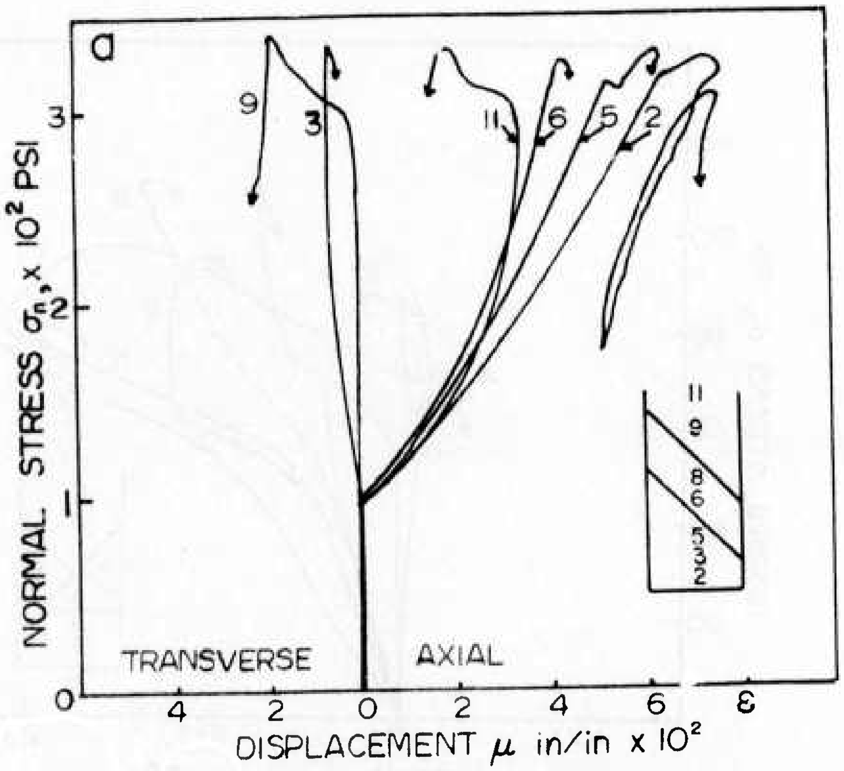


a. Stress-strain behavior of a sample with intersecting joints.

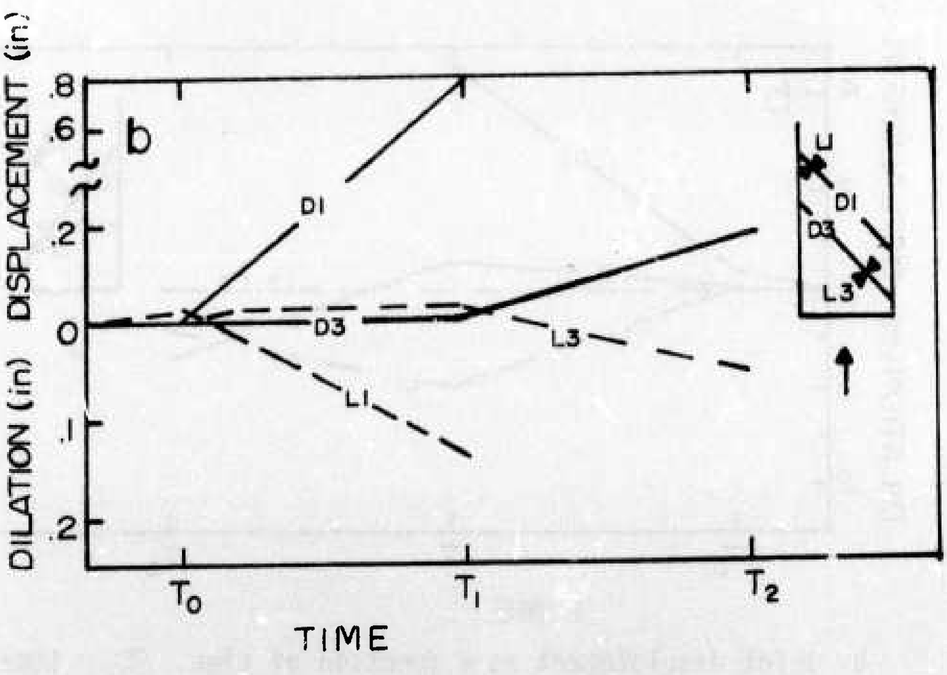


b. Joint displacement as a function of time. T_0 = time of initial shearing; T_1 = time of maximum displacement prior to wedging primary joint; T_2 = time test concluded.

Figure 29. Behavior of specimen with intersecting joints.



a. Stress-strain behavior of a sample with two parallel 45° joints.



b. Displacement as a function of time.

Figure 30. Behavior of specimen with parallel joints.

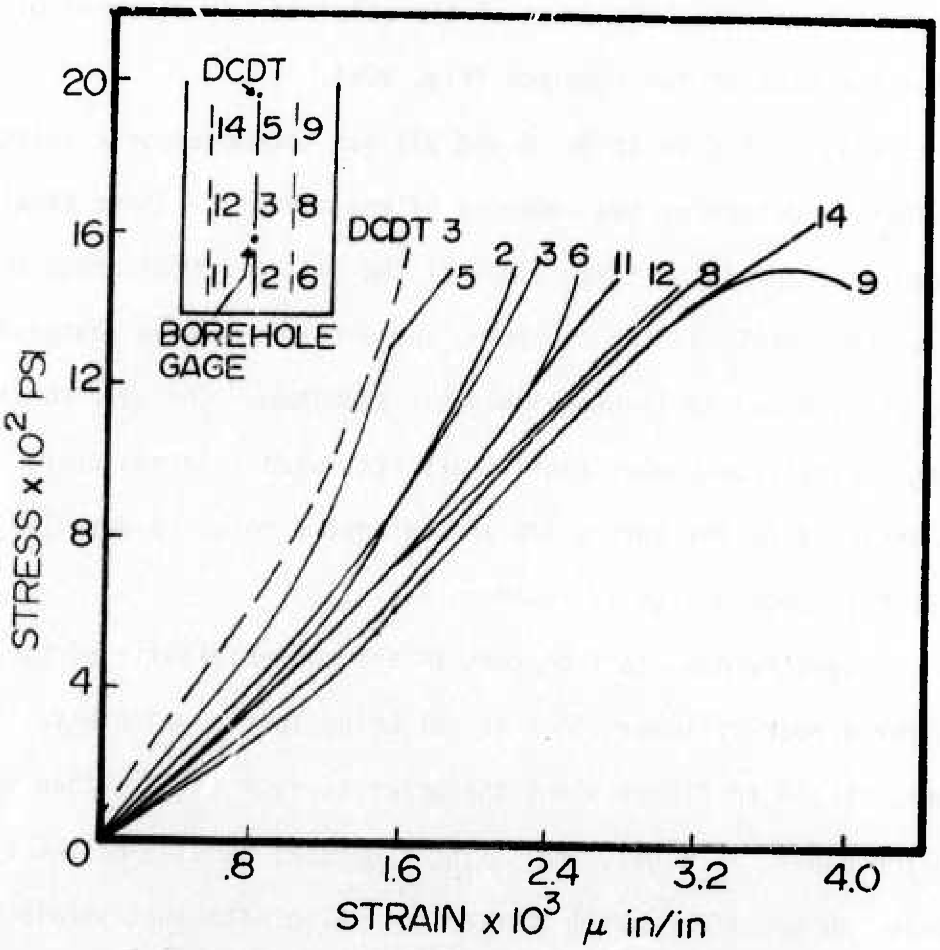
with intersecting joints, the front of the specimen was strained to a greater degree than the back of the specimen (Fig. 30a).

End Effects: Test 14 (Figs. 8 and 31) was conducted on a solid 2.0x3.0-foot specimen to determine the severity of end effects. Three strain gages were placed on each of the three sides of the prism, a DCDT measured axial strain over the length of the specimen, and a borehole gage measured strain at depths of 3, 8 and 13 inches within the specimen. The gage consisted of strain gaged beryllium-copper cantilevers stationed 5 inches apart. The gage was designed to fit into a 3/4 inch diameter hole. A detailed discussion of the borehole gage design if found in Ref. 15.

The stress-strain plots from test 14 are characteristic of the deformation expected for a rock cylinder which is not being loaded uniformly. In this experiment, strain in fibers along the upper surface is less than strain in gages on the other two edges, indicating a general bending of the specimen superimposed on a uniform axial shortening. Also note that strain on surface fibers is lowest at the built-in end (near gage 5) and increases along the length of the specimen. Applying simple beam theory, although it is not appropriate for such a stubby column, we conclude that the moment is highest at the built-in end. Thus, the data suggest that the load at the flat jack contains a downward component in addition to the axial component.

Applied stress would have a downward component if the flat jacks were not grouted in normal to the axis of the specimen or, possibly, the flat jack was not in contact with the face of the specimen over its entire surface. Whatever the cause, the nonuniform strain in this experiment has obscured end effects resulting from changes in lateral constraint, should they be present.

The stress-strain curves from individual gages have the same general



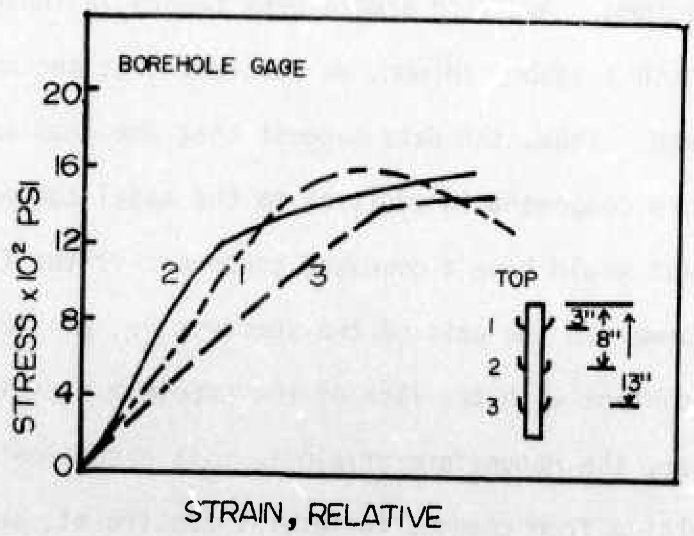


Figure 31. Stress-strain behavior of a solid specimen to study uniformity of strain.

shape that would be expected for rock of this type. Also values from comparable locations (6 and 11, 8 and 12, 9 and 14) are approximately equal. This aspect of the results is encouraging.

DCDT data agree with the explanation of data from the strain gages above. The DCDT is located some 2 or 3 inches above the upper surface of the specimen, so that strain resulting from bending is somewhat greater than that on the surface. The compressive strain from the DCDT should be less than that from the surface gages, as observed.

Borehole data agree only partially with the explanation above. Strain data, which is only relative, from 3 is greater than that from 1 and 2, as would be expected from downward bending. Strain from 1 should be less than that from 2, however, and the opposite is observed. We have no explanation for this.

In summary, the data are characteristic of a cantilevered strut loaded in axial compression with a superposed downward bending. Perhaps the flat jack was not positioned normal to the axis of the prism, or perhaps the load was not uniform over the face. In any event, the nonuniform strain seems to be the result of bending rather than end-effects due to constraint at the ends of the specimen.

Data from other experiments in this test series and those from a previous series (Ref. 15 and 16), however, lead us to believe that most of the samples tested have been loaded uniformly.

Sandstone Specimens: A 2.0x3.0-foot sandstone specimen was prepared using the new portable drill rig (Fig. 12). The site was situated near Park City, Utah, about 30 miles east of Salt Lake City on bedding surfaces of Nugget sandstone which dipped between 10-50° depending on locality. The primary objective of these tests was to prove the feasibility of this rig on

sloping surfaces. Stress-strain data from test 15 indicates a maximum stress of 1.59 ksi. The specimen failed along one of the bedding planes oriented parallel to the sloping surface. As stress was increased the beds began separating and the specimen buckled. Maximum stress is much lower than would be expected for a small homogeneous sample without bedding. The specimen after testing is shown in Fig. 32.

Laboratory Tests

Laboratory direct shear tests were conducted on 6x6-inch samples cut from 6-inch cores taken along the same joints as tested in-situ. Additional tests were conducted on NX core samples which contained artificial joints formed by diamond sawing or breaking in a Brazilian tension test. Uniaxial stress tests were also conducted on unjointed NX cores. Results from all the laboratory tests are summarized in Table III.

Two direct shear samples (6x6 inches) were usually obtained from each core. One was pulled in tension to determine an initial joint cohesion and subsequently profiled (P); the other was sheared (S) in an undisturbed condition. The process of pulling in tension, profiling, and repositioning did not effect the frictional properties of specimens 8cp and 8cs (Fig. 33) as the maximum and residual shear stresses are reasonably close for each specimen at two different normal stresses. This lends confidence in combining the data from virgin and profiled specimens. Tensile strengths of the natural joints ranged from .3 to 28 pounds or always less than 1 psi.

Effect of Normal Load on Surface Modification: The effect of normal load on surface modification during shearing is readily apparent in Figs. 34, 35 and 36. At low normal stresses natural joints are modified slightly. Development of slickensides and gouge material increases markedly with increasing normal stress. In some cases the development of Riedel shears

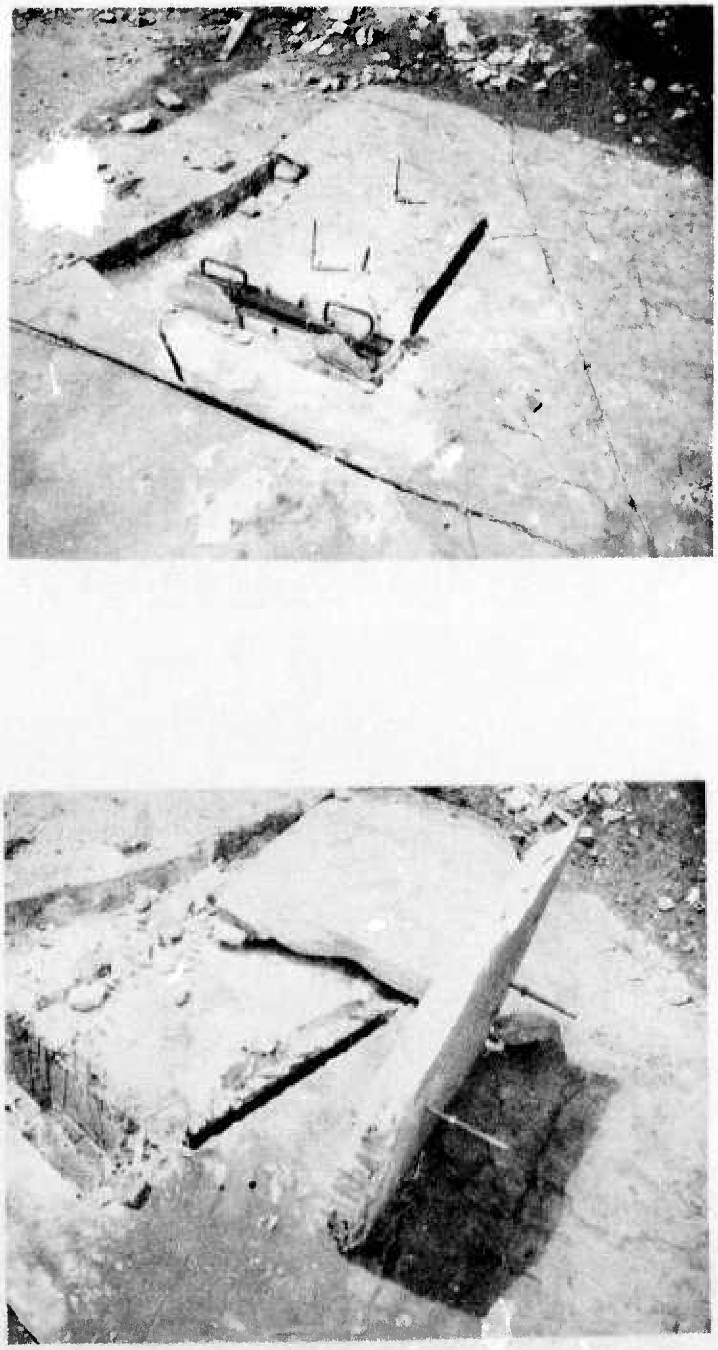


Figure 32. Post test sandstone specimen

Table III

Laboratory Test Program

Direct Shear

Test No.	Sample No.	Normal Stress psi	Shear Stress I*	Shear Stress M	Shear Stress R	Coefficient of Friction I	Coefficient of Friction M	Coefficient of Friction R
1	2s**	1000	370	810	750	.37	.74	.67
2	17s	70	20	20	20	.29	.29	.29
		400	200	270	270	.50	.64	.64
		730	320	450	400	.44	.62	.55
3	16as	100	50	190	190	.50	1.13	1.13
4	11s	940	760	760	640	.81	.77	.68
5	14s	170	80	120	100	.40	.71	.68
6	8cs	180	50	120	100	.28	.67	.59
		320	120	180	180	.38	.56	.56
7	6s	272	150	150	110	.56	.56	.40
8	1s	350	215	250	250	.61	.68	.62
		600	250	370	370	.42	.62	.62
		900	450	540	490	.50	.60	.53
9	10s	950	825	825	430	.87	.87	.45
10	2as	650	420	460	430	.65	.57	.51
		930	380	500	500	.41	.54	.54
11	19s	170	80	150	130	.47	.88	.72
		320	300	320	320	.94	1.00	1.00
12	2p	50	25	50	40	.50	1.00	.80
13	8cp	180	95	125	120	.53	.69	.67
		320	170	190	190	.53	.59	.59
14	11p	874	480	485	380	.55	.54	.43
15	6p	280	66	160	160	.24	.57	.57
16	19p	1521	963	1120	1075	.63	.72	.71
17	16p	90	43	40	40	.50	.66	.45
		310	120	170	170	.39	.44	.44
		600	310	390	335	.52	.65	.54

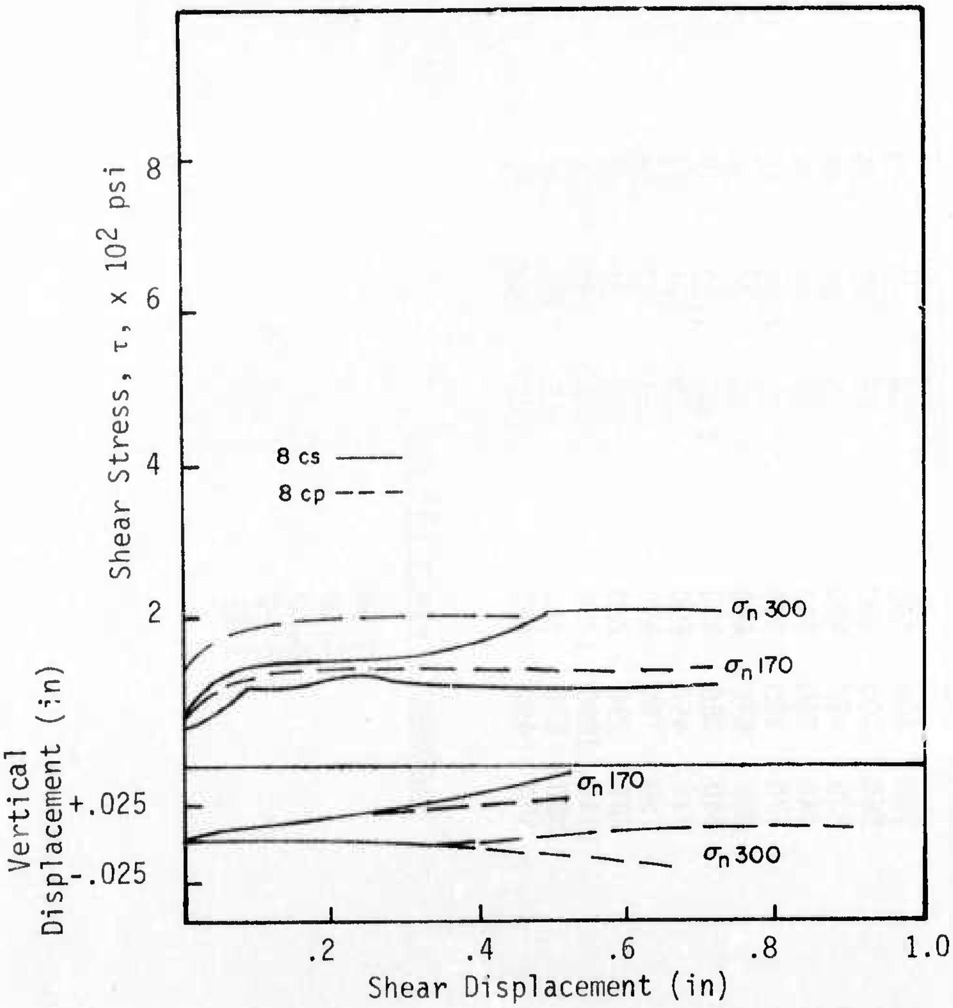
Table III (Continued)

Test No.	Sample No.	Normal Stress psi	Shear Stress I*	Shear Stress M	Shear Stress R	Coefficient of Friction I	Coefficient of Friction M	Coefficient of Friction R
18	2ap	640	280	400	400	.44	.63	.63
		910	560	700	690	.62	.76	.76
19	3A (Sawcut)	600	330	420	420	.55	.62	.62
		950	640	750	750	.67	.75	.79
20	2B (Brazil)	320	270	350	300	.75	1.09	.88
		600	380	490	490	.63	.75	.75
21	3B (Sawcut)	340	340	380	400	1.00	1.05	1.18
		600	315	490	490	.53	.71	.81
22	2C (Brazil)	950	750	780	580	.54	.82	.59
23	3C (Sawcut)	950	620	790	780	.65	.81	.81
		1230	1040	1090	1050	.85	.89	.85
24	2I (Brazil)	650	580	635	560	.89	.98	.86
		950	400	490	490	.42	.52	.52

Uniaxial Stress		Maximum Stress x 10^3 psi
25	1A	3.95
26	1B	5.40
27	1C	4.33
28	1H	6.92
29	1I	7.69

* I-initial M-maximum R-residual

** Tests 1-18 on natural joints; s-virgin, p-profiled



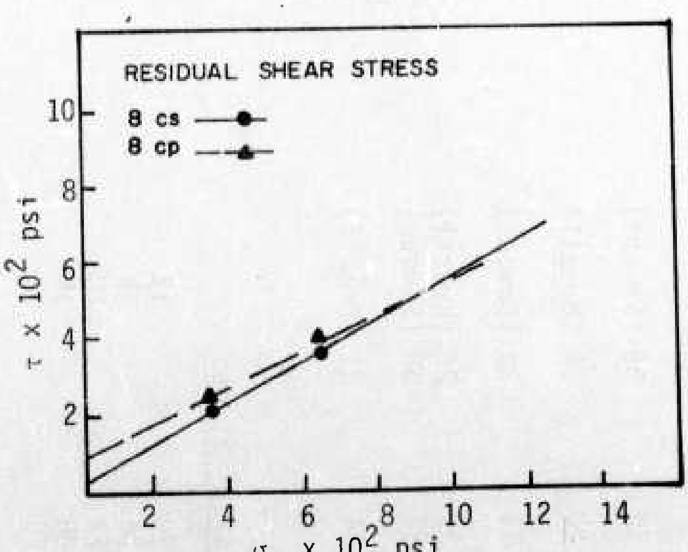
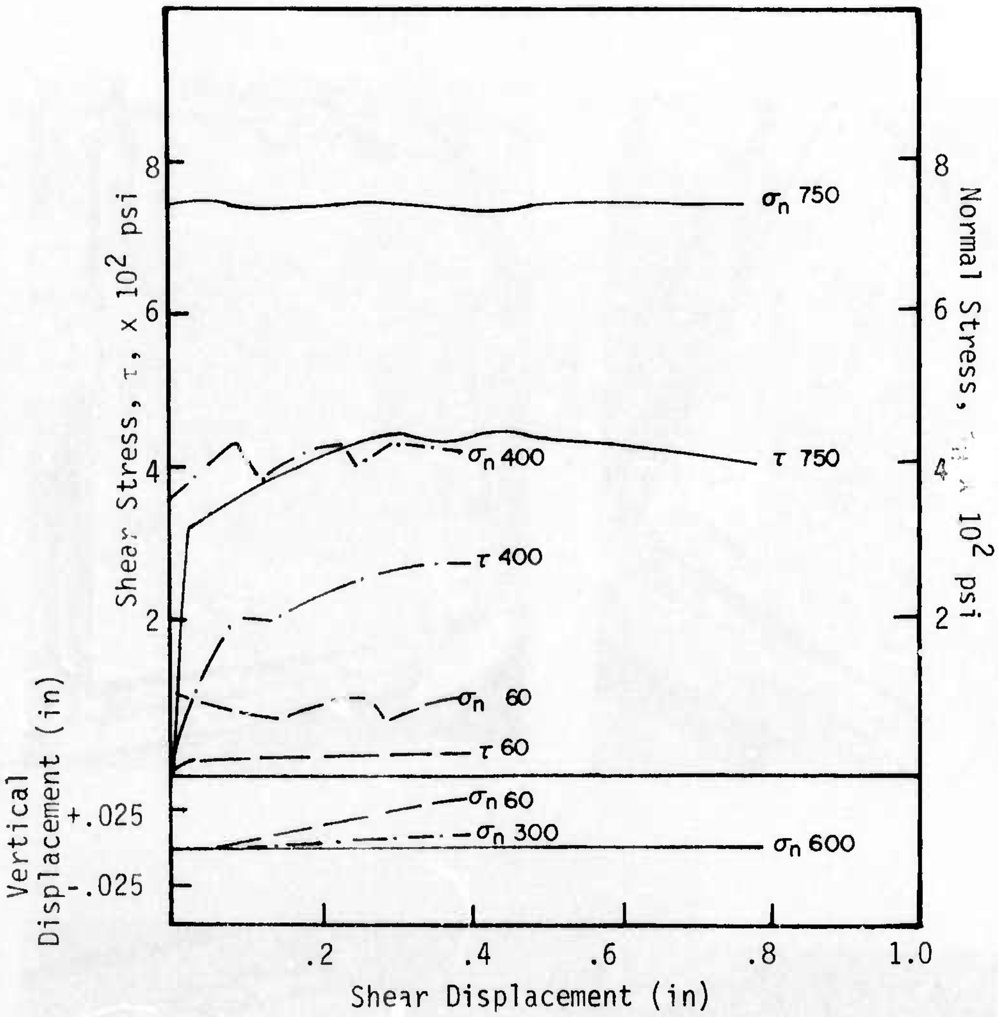


Figure 33. Two specimens tested from the same core. 8cp pulled in tension, profiled and sheared; 8cs tested in the undisturbed state.



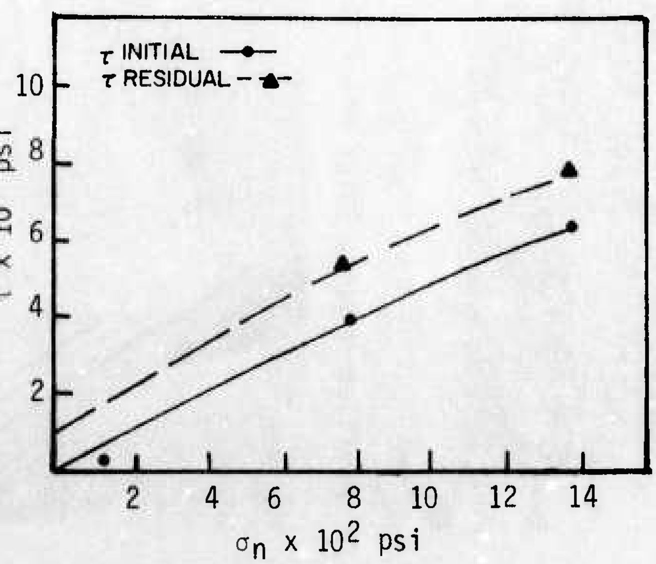
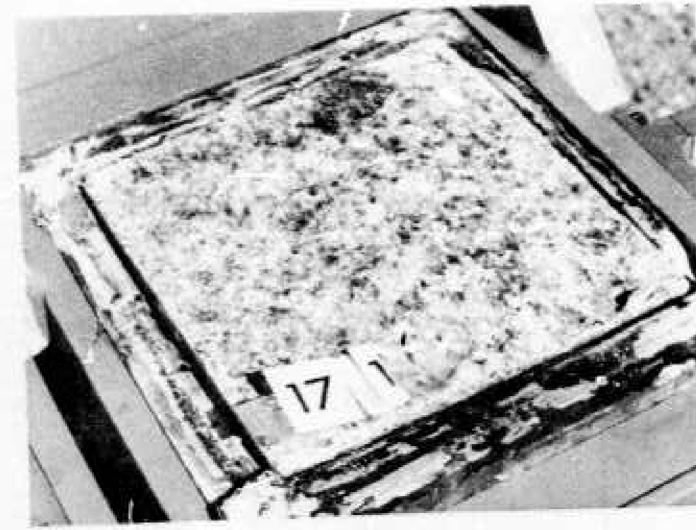
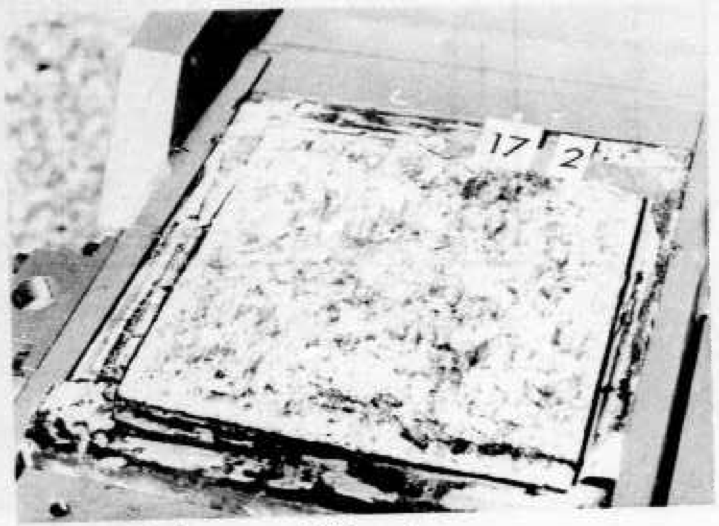


Figure 34. Frictional properties of specimen 17s at different normal stresses.

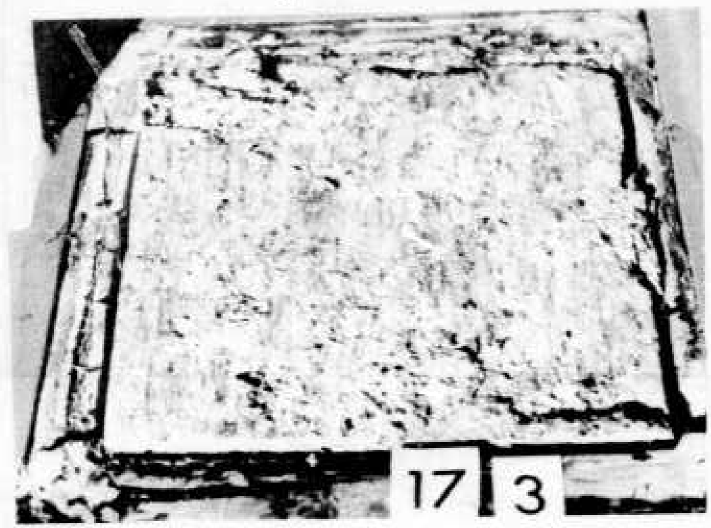
17 Profiled natural joint prior to testing



17-1 σ_n = 70 psi



17-2 σ_n = 400 psi



17-3 σ_n = 700 psi. Note development of slickensides and gouge.

Figure 35. Specimen 17 - Surface modification of a natural joint (6x6 in) as a function of normal stress.

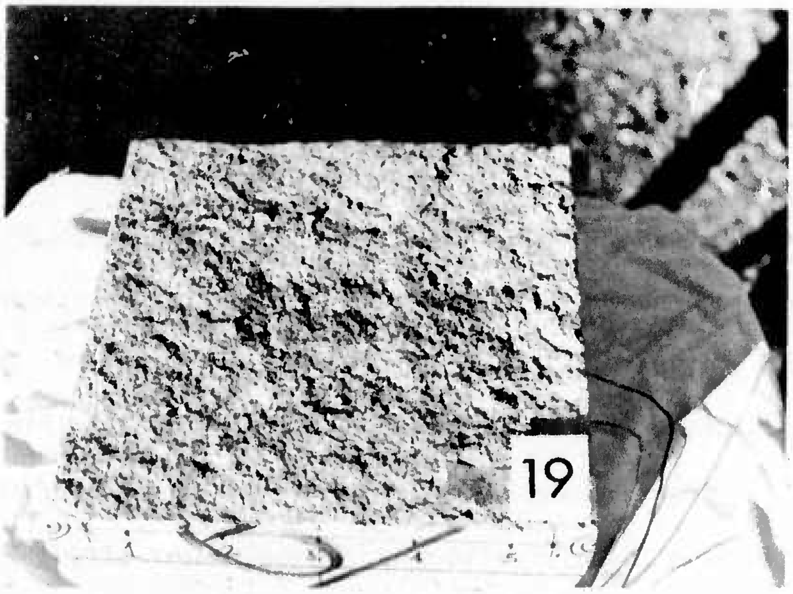


Figure 36. Specimen 19p - natural joint surface and after shearing at σ_n = 1521. Specimen size 6x6 inch.

were noted oriented normal to the slickensides. Profiles of surfaces before and after testing illustrate the degree of modification and the buildup of a gouge zone along the joint surface especially at the near end of specimen (Figs. 37 and 38). Modification is greater at higher normal stresses, as would be expected.

The Effect of Load History: Load history clearly plays an important role in determining the magnitude of the initial shear stress and the degree of surface modification. This effect was analyzed on natural joints (Figs. 39 and 40), on sawcuts (Fig. 41) and on Brazilian surfaces (Fig. 42). Comparison of specimens 1s and 16p indicate that a virgin surface tested at σ_n=350 psi slips at a significantly high initial shear stress (τ_i=215 psi) than a surface which had been previously sheared at 90 psi. Initial shear stress of this latter specimen was about 120 psi. Other examples include (Table II) specimen 1s with τ_i=215 psi, σ_n=350 psi compared to 8cs with τ_i=120 psi, σ_n=320 psi. Specimen 8cs had been sheared previously at σ_n=180 psi. At higher normal stress (900 psi) the same trend still holds. Specimens 11s and 10s were both tested at σ_n=940 psi with resulting τ_i=760 and 825 psi, respectively. Specimens 2as, 1s and 2ap were all tested in the normal stress range of 900-930 psi but with prior loading history. Initial shear stresses equaled 380, 450 and 560 psi, respectively, significantly lower than for specimens 11s and 10s. In tests with sawcuts and Brazilian surfaces, "virgin" surfaces require a high initial shear stress and greater displacement than surfaces tested at similar normal stresses but that have been previously sheared at lower normal stresses (Fig. 41). In samples with a prior history, the asperities have been modified and slickensides and a layer of gouge developed which lowers frictional resistance. This is especially significant where initial surfaces are perfectly mated as in the case of

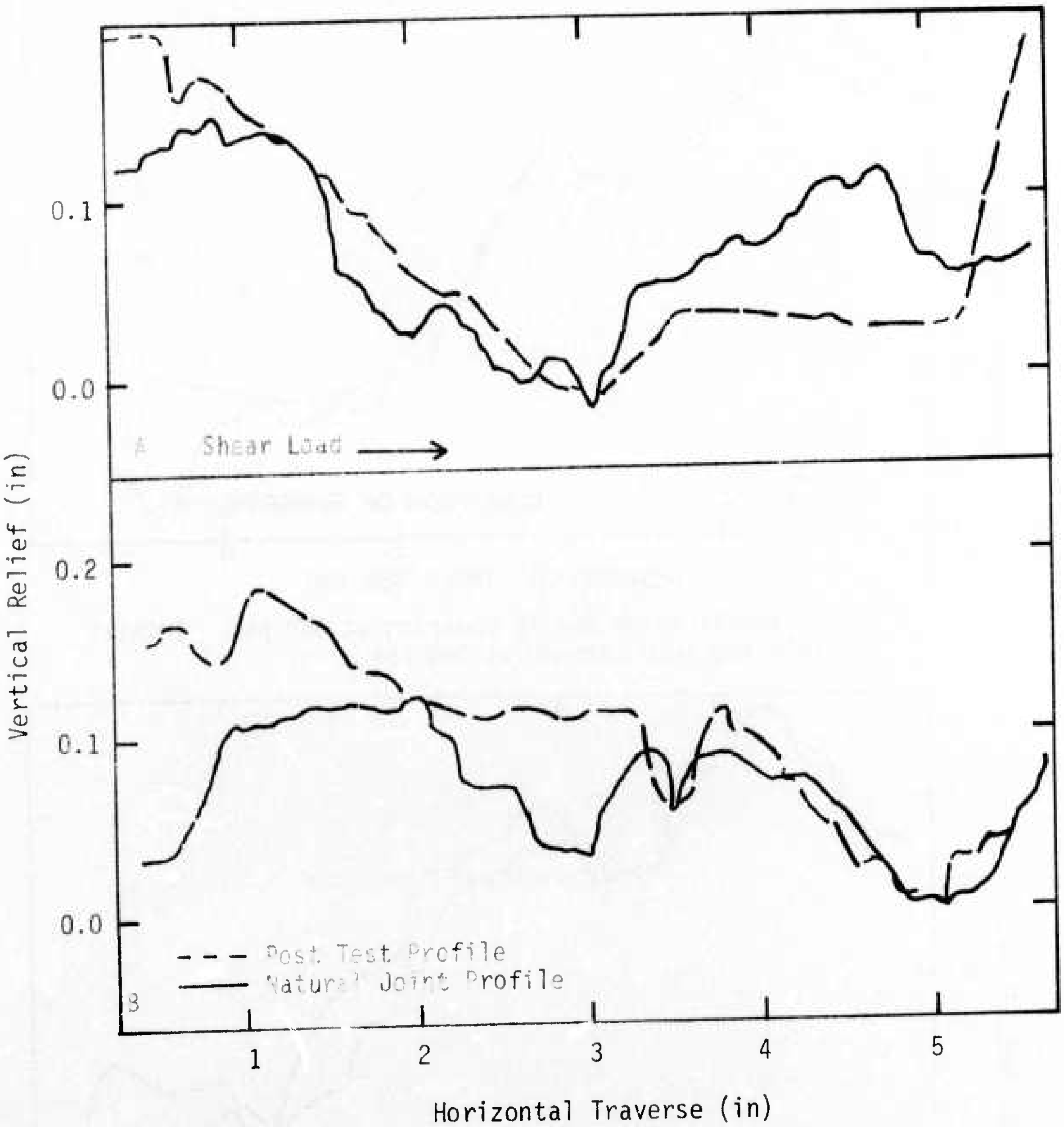
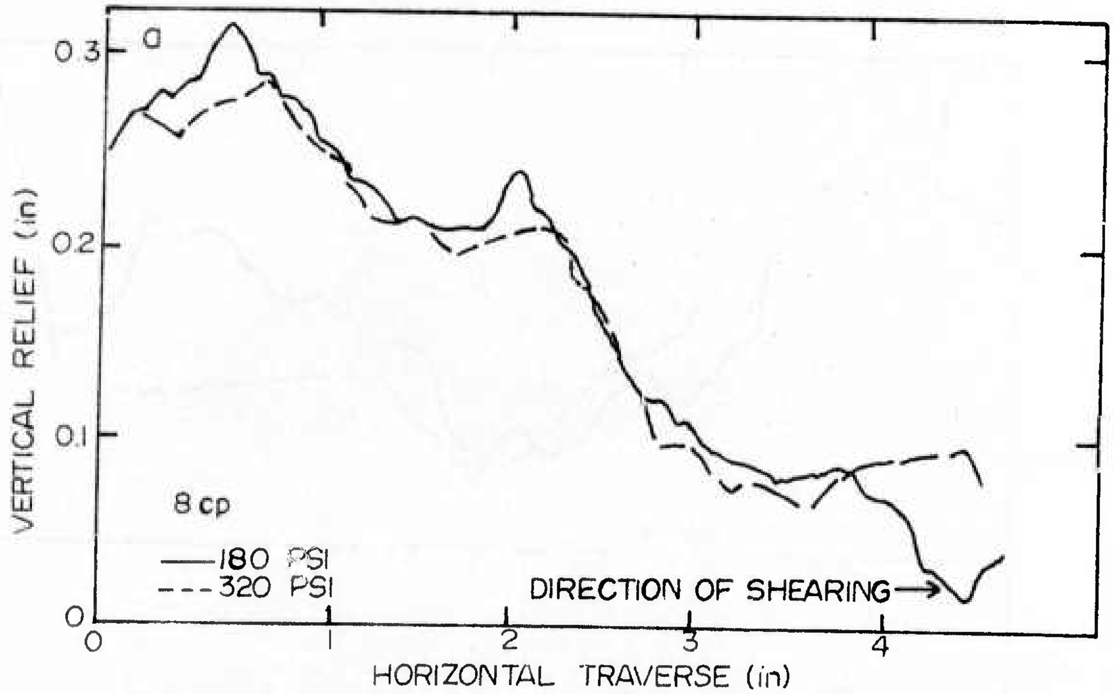
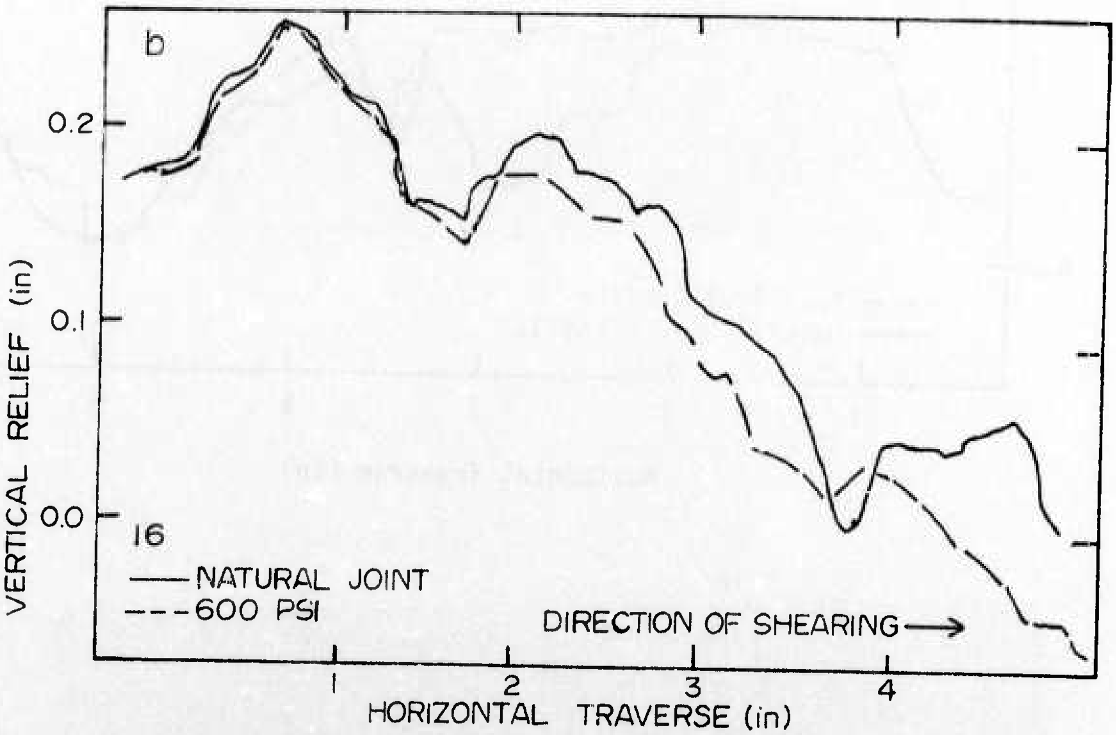


Figure 37. Joint modification due to shearing at 600 psi normal stress. Two different profiles on specimen 2ap.

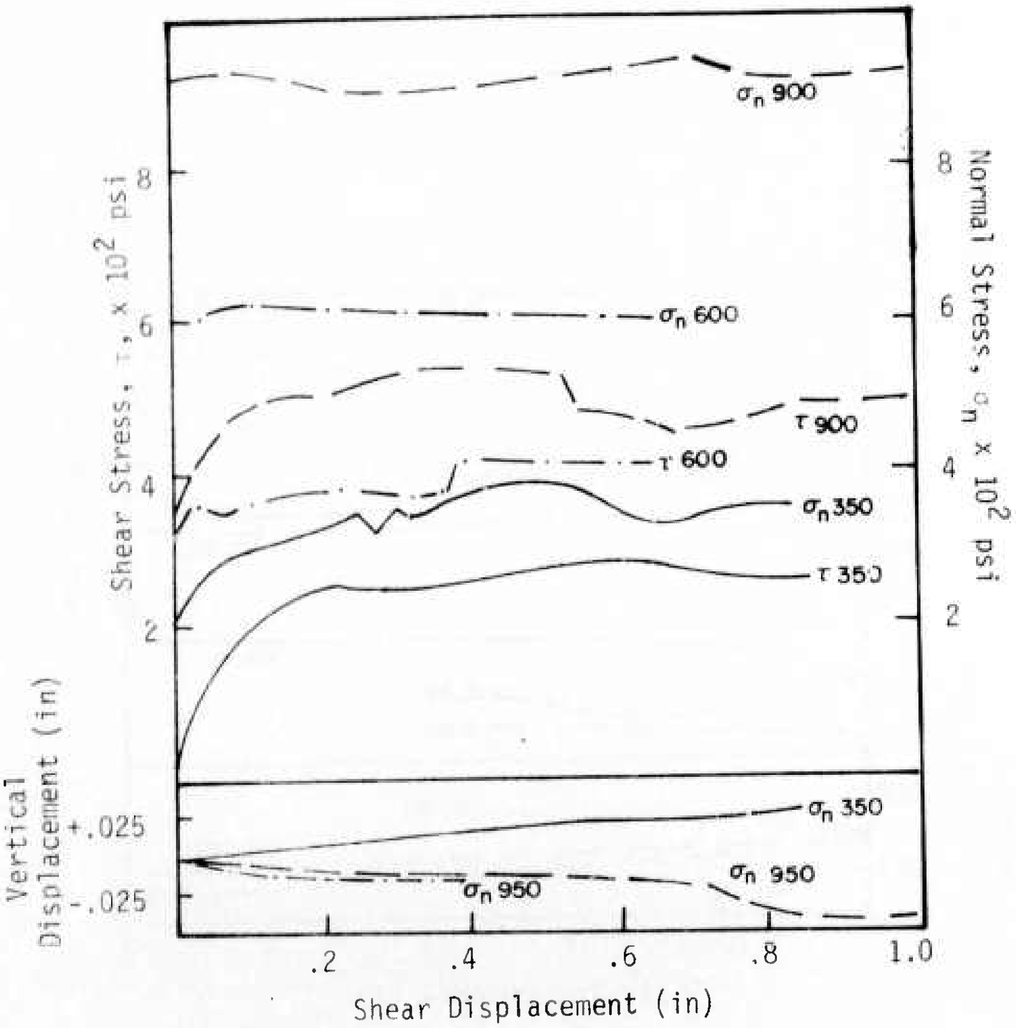


a. Joint modification due to shearing at 320 psi. Initial profile had been sheared at 180 psi.



b. Natural joint and joint modification through a sequence of tests at 75, 300 and 600 psi.

Figure 38. Joint modification as a function of shearing.



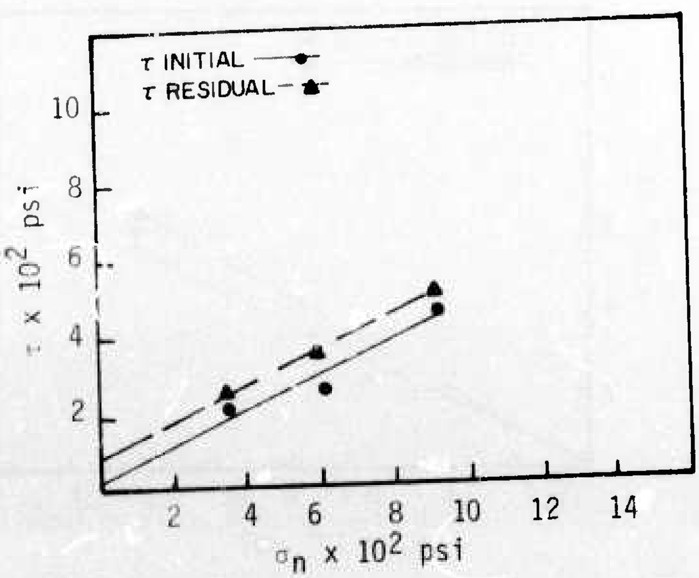
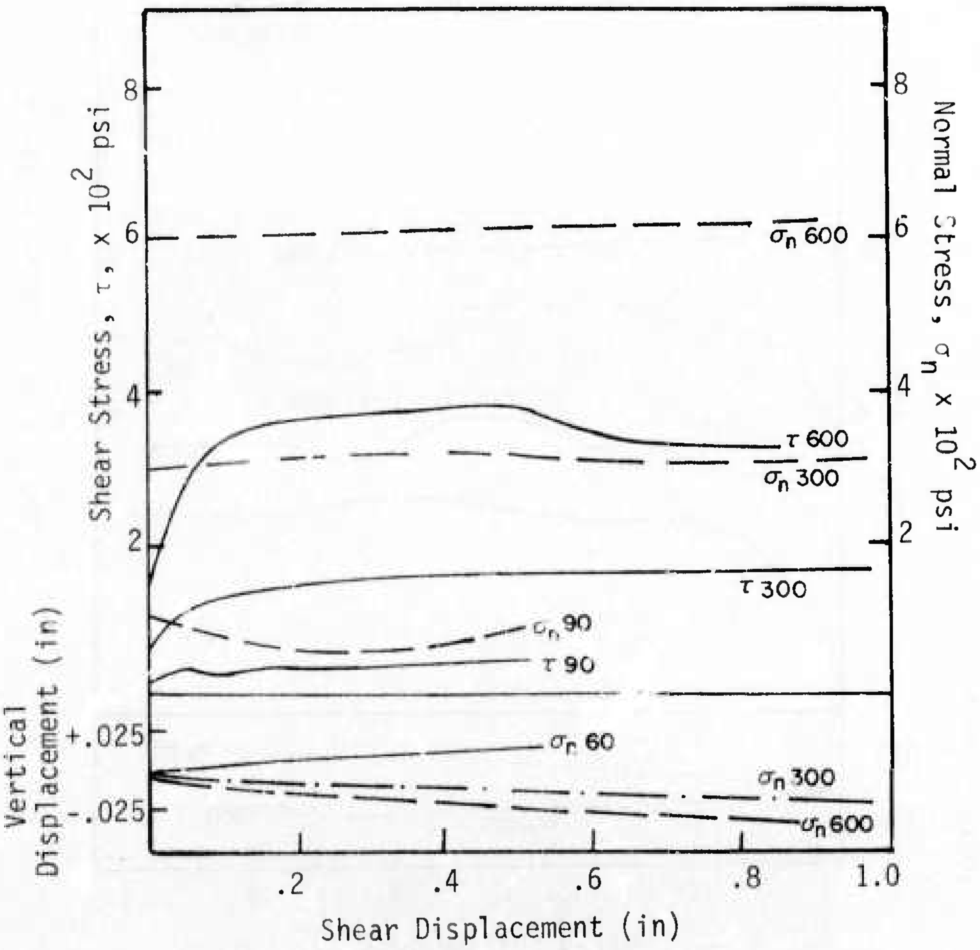


Figure 39. Shear stress-shear displacement, normal stress-shear displacement, vertical displacement-shear displacement, and shear stress normal stress behavior for specimen 1s at different normal stresses.



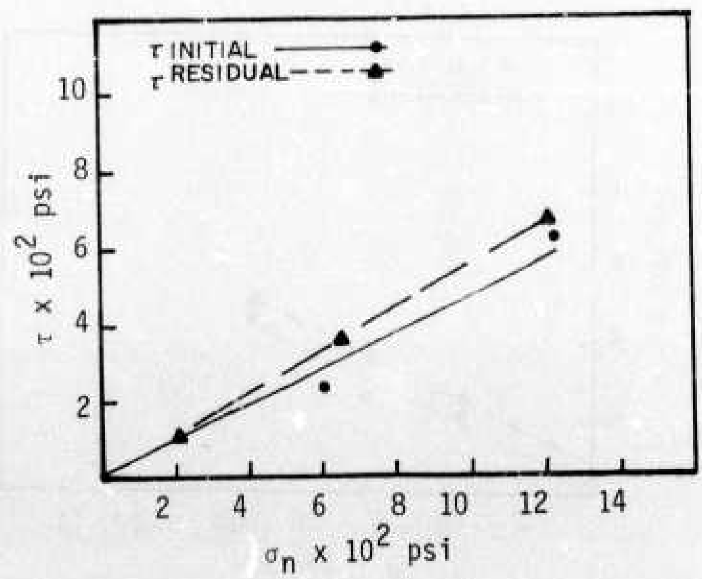


Figure 40. Shear stress-shear displacement, normal stress-shear displacement vertical displacement-shear displacement, and shear stress normal stress behavior for specimen 16p at different normal stresses.

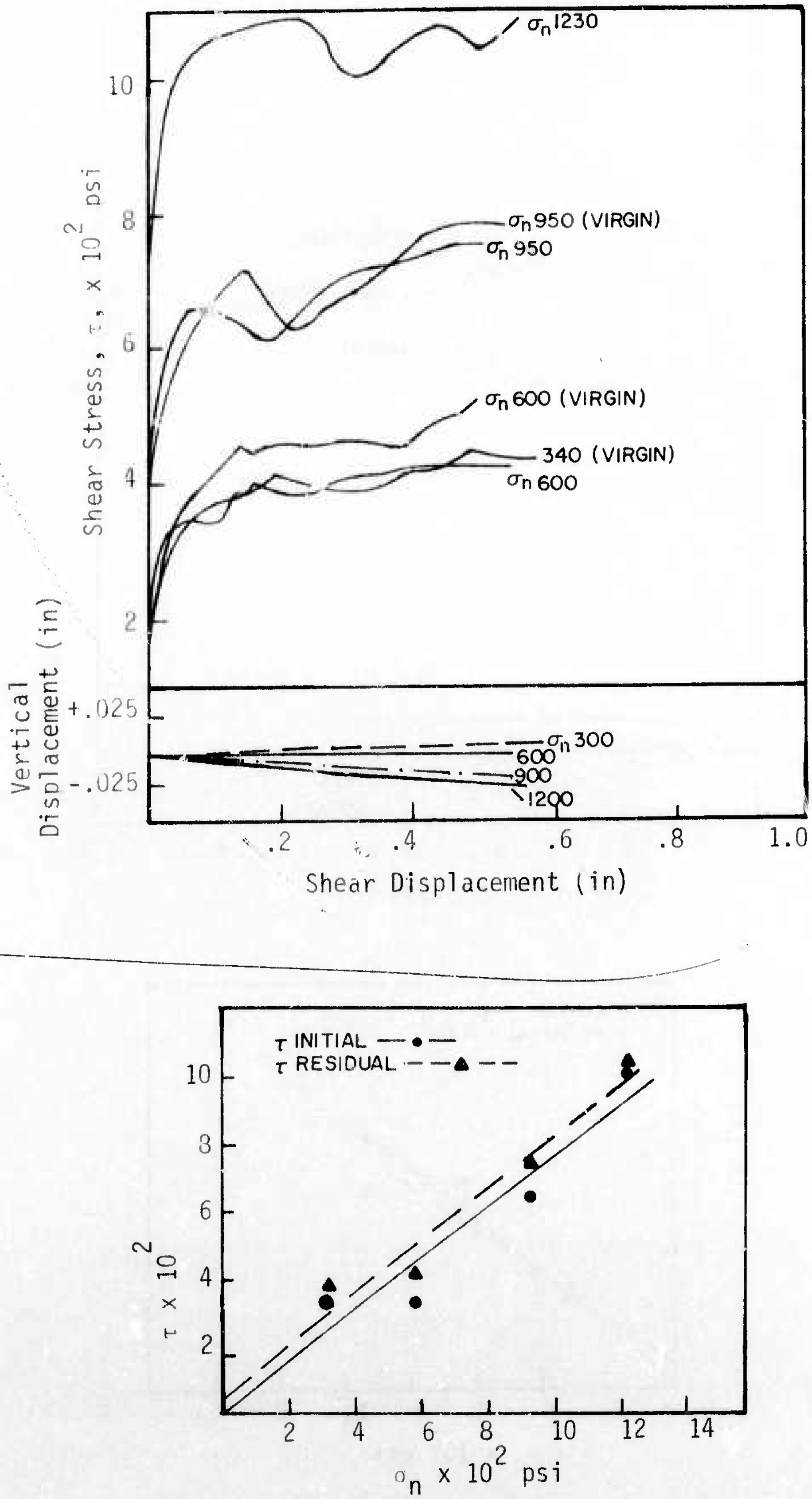


Figure 41. Frictional properties of sawcut surfaces.

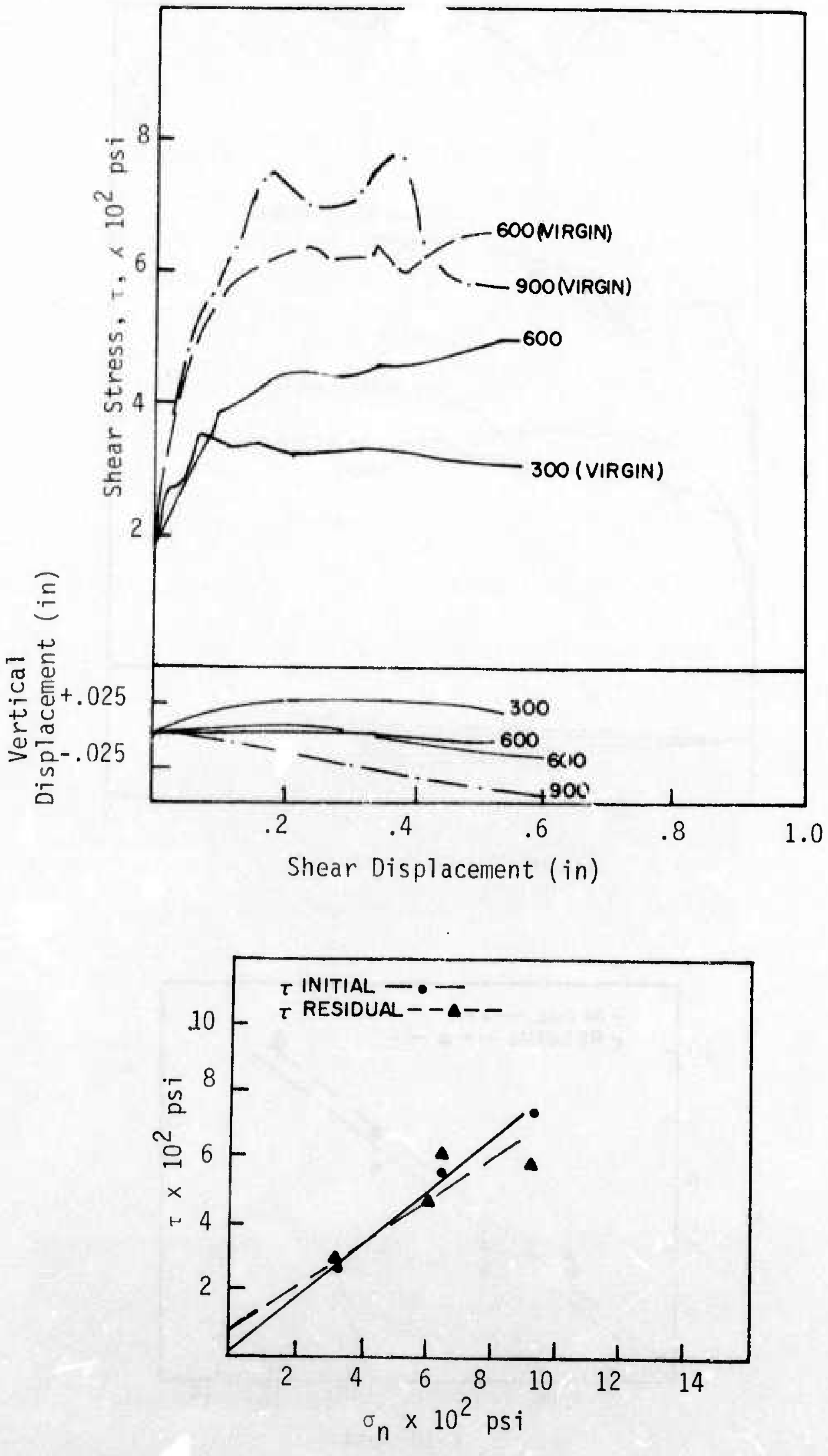


Figure 42. Frictional properties of Brazilian surfaces.

sawcuts and Brazilian surfaces.

Normal Load Variability: Development of a servo-controlled direct shear machine allowed for the first time complete control of the normal load throughout a test. In most tests the normal load was automatically held constant at a predetermined value. For some tests the normal load was allowed to vary during the test. This case simulates the constant displacement conditions for most other studies. Normal load was monitored for all tests. Accuracy of the normal load was about ±10 psi. The influence of varying the normal load is seen in Figs. 43, 39 and 40. Shear stress values and the character of the shear stress-displacement curve reflects the variability in the normal load.

Effects of Surface Roughness and Initial Contact Area: Tests were conducted on artificial joints of two different roughnesses over a range of normal stresses from 300 to 1200 psi. Initial roughness as determined by the profilometer, was approximately 700 microinches for the sawcut and about 0.1 inch for the Brazilian surface (Figs. 43 and 44). For both the sawcuts and Brazilian surfaces, shear stress increases rapidly with normal stress (Figs. 41 and 42). Vertical displacement noted during a test also appears to be a function of normal stress. At low normal stresses (300 psi or less) the joint dilates during displacement, while at normal stress greater than 600 psi the joint compresses for both sawcuts and Brazilian surfaces. Initial profiles and subsequent modification of these two surfaces (Figs. 45 and 46) indicates that, as expected, the Brazilian surface is modified markedly during the test.

Comparison of these two surfaces with the natural joint surfaces (Fig. 47a) indicates that the initial shear stress required for mobilization is lower for natural joints than for either sawcut surfaces or Brazilian surfaces.

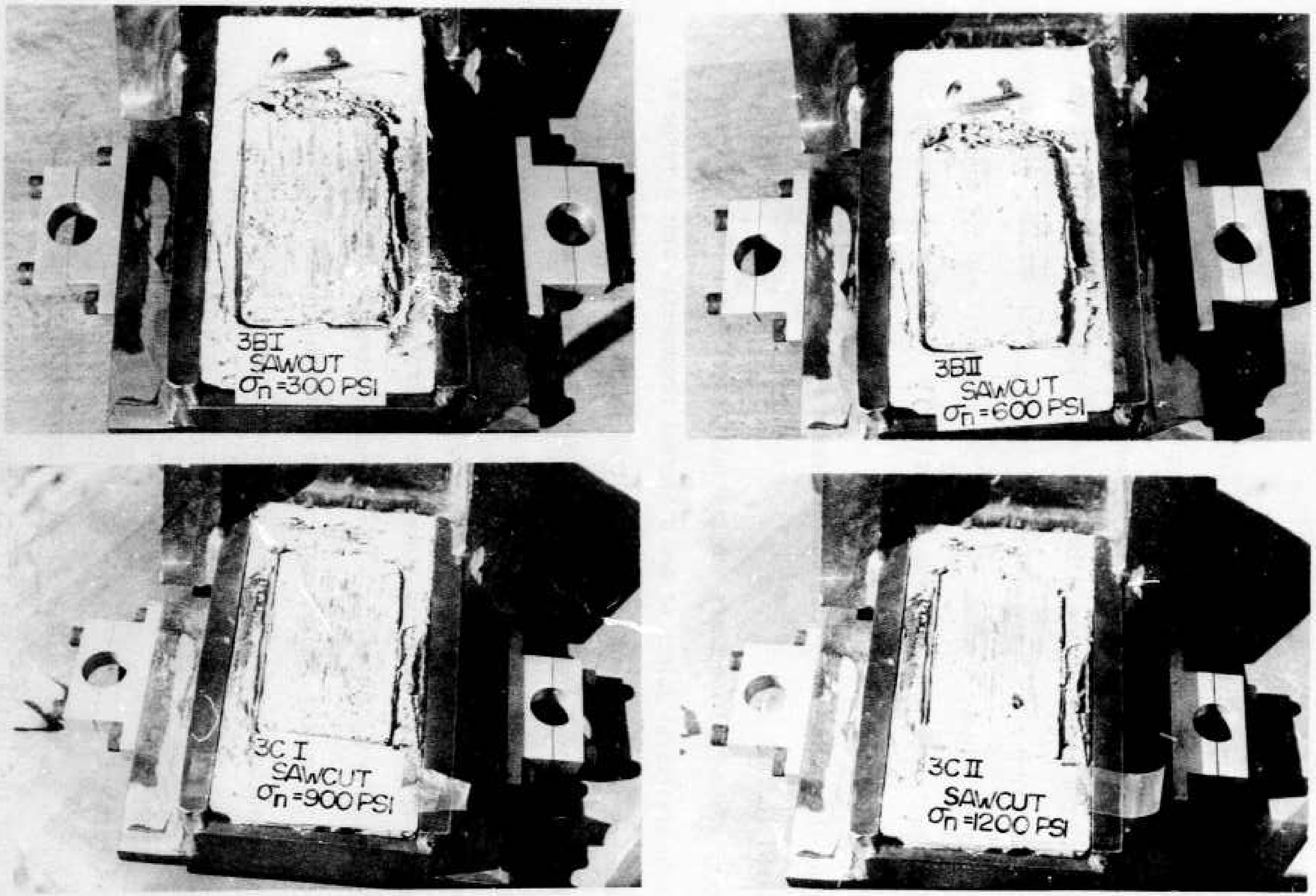


Figure 43. Sawcut Specimens - Surface modification as a function of normal stress. Specimen size 2.125x3.80 in.

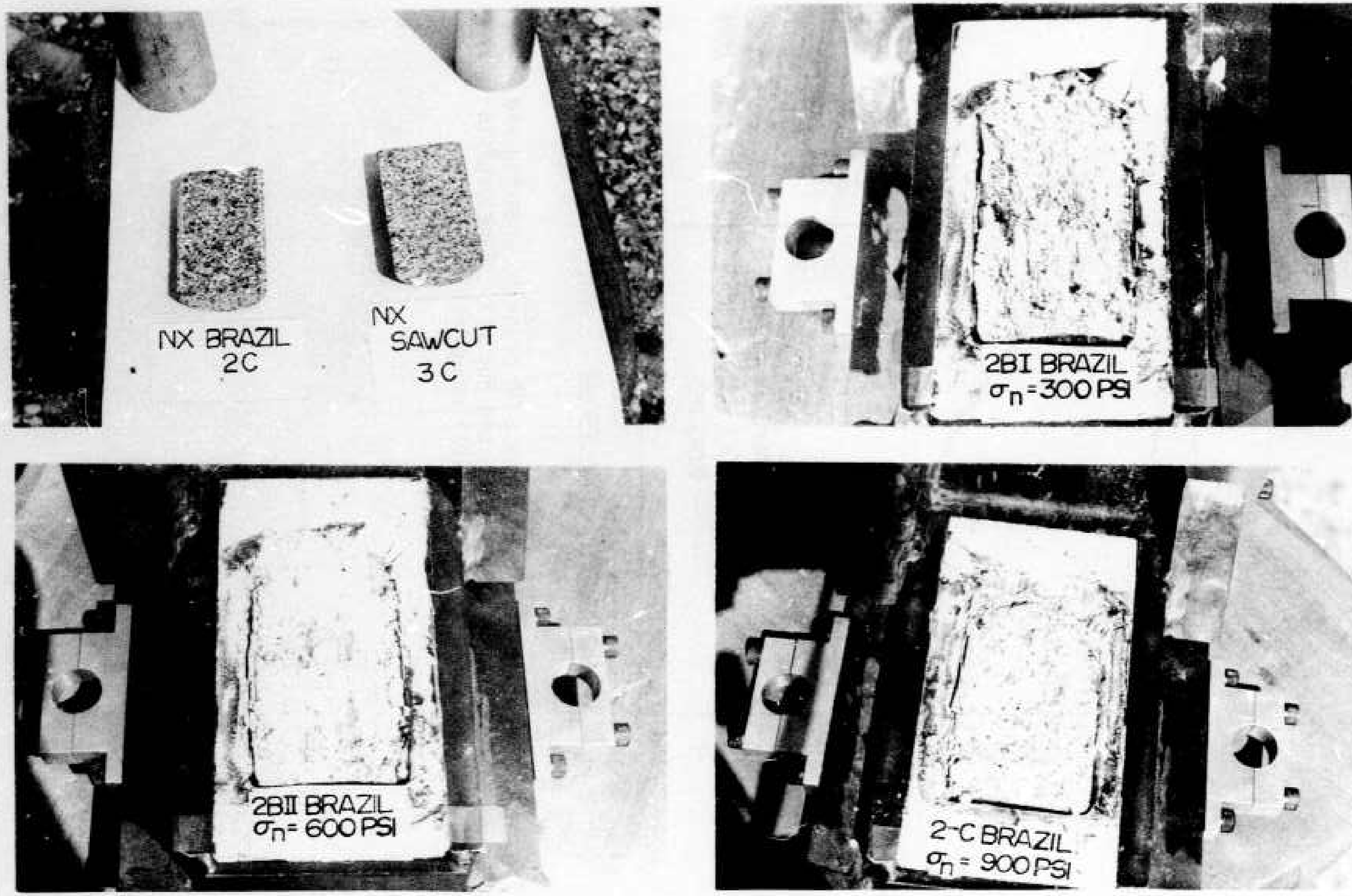


Figure 44. Brazil Tests - Surface modification as a function of normal stress. Specimen size 2.125x2.80 in. Note development of slickensides and gouge with normal stress.

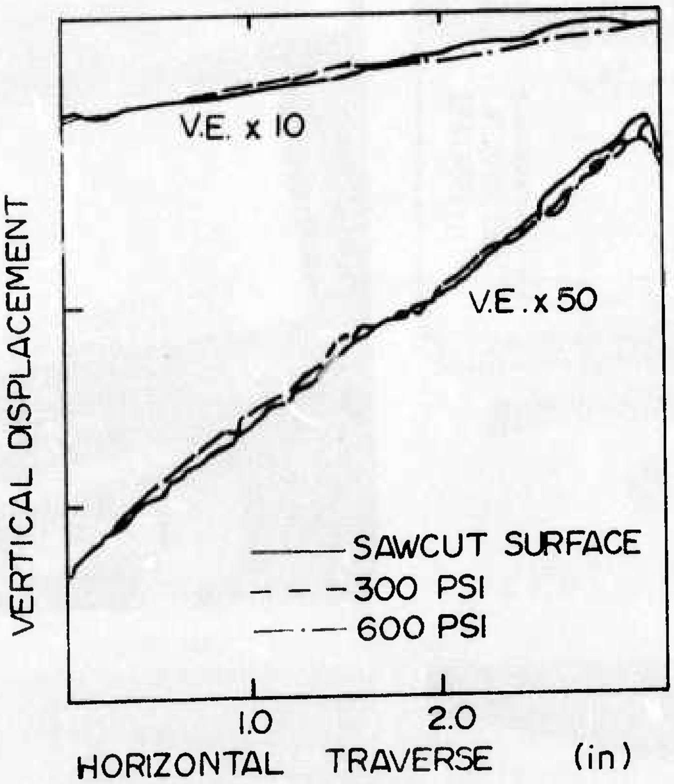


Figure 45. Profile of sawcut surface 3B prior to shearing and after shearing, at 300 and 600 psi. Same profile at two different vertical exaggerations.

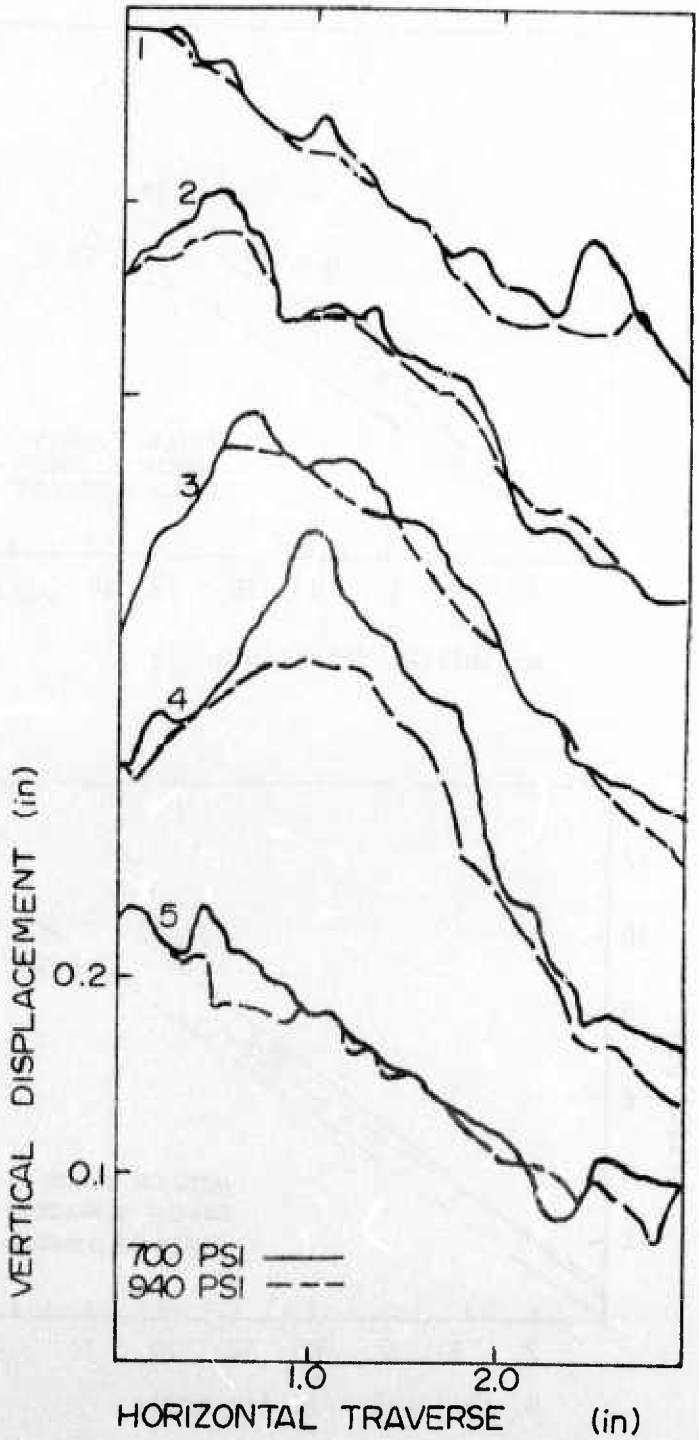
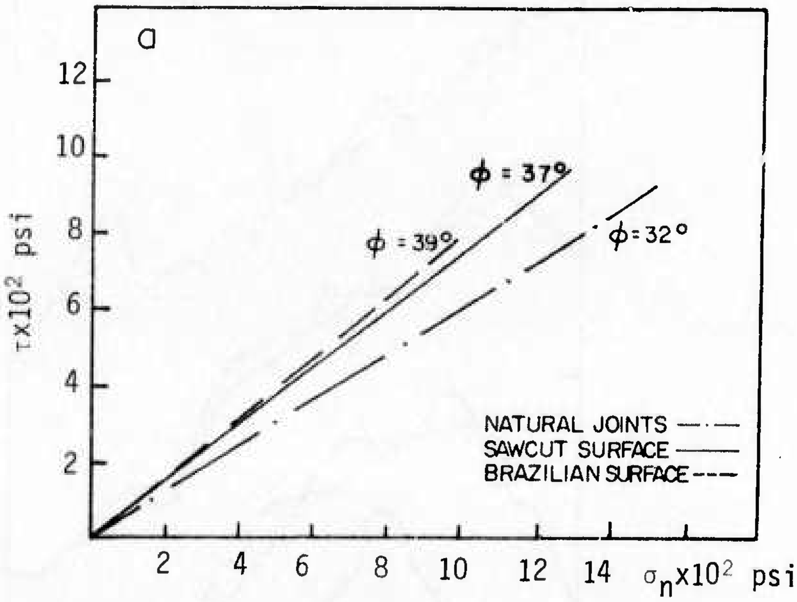
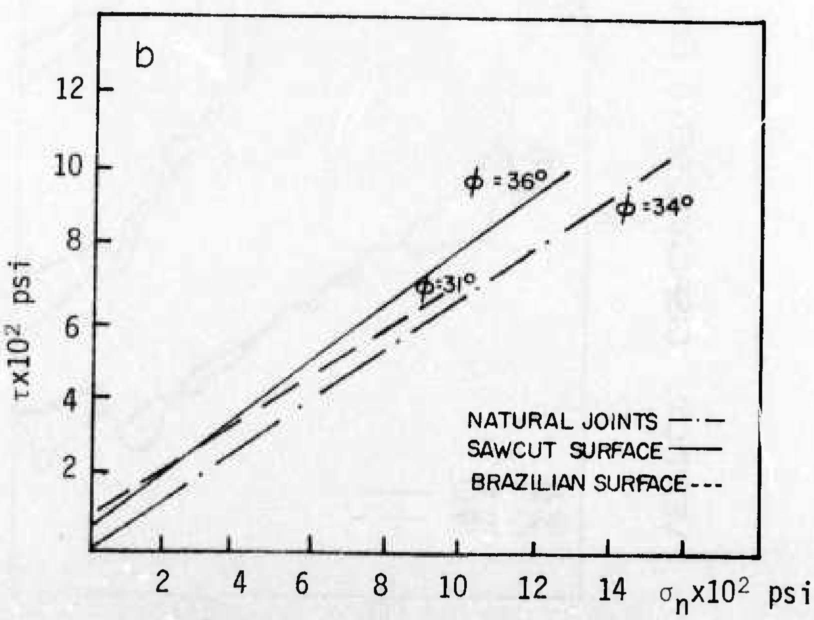


Figure 46. Profiles of Brazilian surface 2I after shearing at 700 and 940 psi. Vertical exaggeration X 10.



a. Initial friction angle



b. Residual friction angle

Figure 47. Frictional properties of natural joints, sawcut surfaces and natural joints.

This was true regardless of the normal stress applied. The displacement required before the initial shear stress is attained is also greater. This could have been the result of the small initial contact area (10-15%) or of low strength filling material in the natural joint. Based on initial shear strengths the friction angle for the three surfaces was 30° for the Brazilian surface, 37° for the sawcut surface and 32° for the natural joint surface. The residual friction angles (Fig. 47b) indicate that the geometric effect has disappeared at displacements of 0.5 inch and greater. Natural joints do not have a significant residual "cohesion" while both the artificial surfaces have residual "cohesions" of approximately 100 psi.

Frictional Properties Along a Single Joint: The variation in properties along a single natural joint was studied in detail along two of the primary joints (Fig. 5). It appears that the shear stresses resulting from a given normal stress are reasonably consistent among the cores tested, that is, the shear stress is about that expected for a given normal stress (Figs. 48 and 49). An exception would be the higher τ_i and τ_r for a specimen tested at σ_n=620 than a specimen tested at σ_n=620. The vertical displacements exhibited by various specimens are also consistent with data from artificially prepared surfaces where the sample initial roughness was the same for each specimen. The natural joint shows a dilation at lower normal stress but not higher normal stresses. The data scatter in the failure envelope (Fig. 48) is about what is expected from the same suite of specimens tested in direct shear.

Uniaxial Stress Tests: Uniaxial stress tests were conducted on several NX specimens cored from three areas adjacent to the in-situ specimens. Maximum stress of the samples from the area in which the single jointed specimens were located ranged from 6.9 to 7.7 ksi and averaged 7.3 ksi. Average Young's modulus was 1.0×10^6 psi and average Poissons ratio was .18

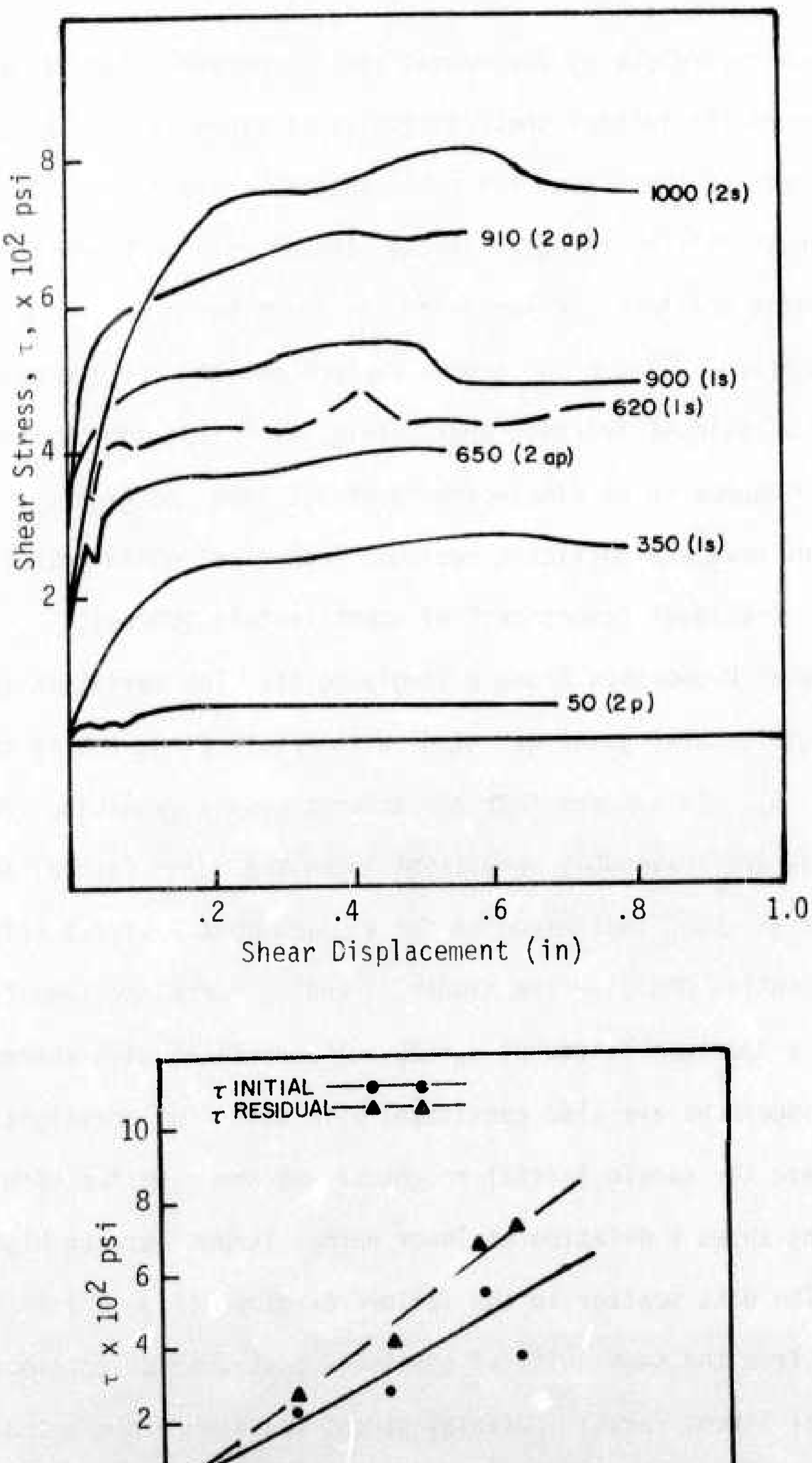
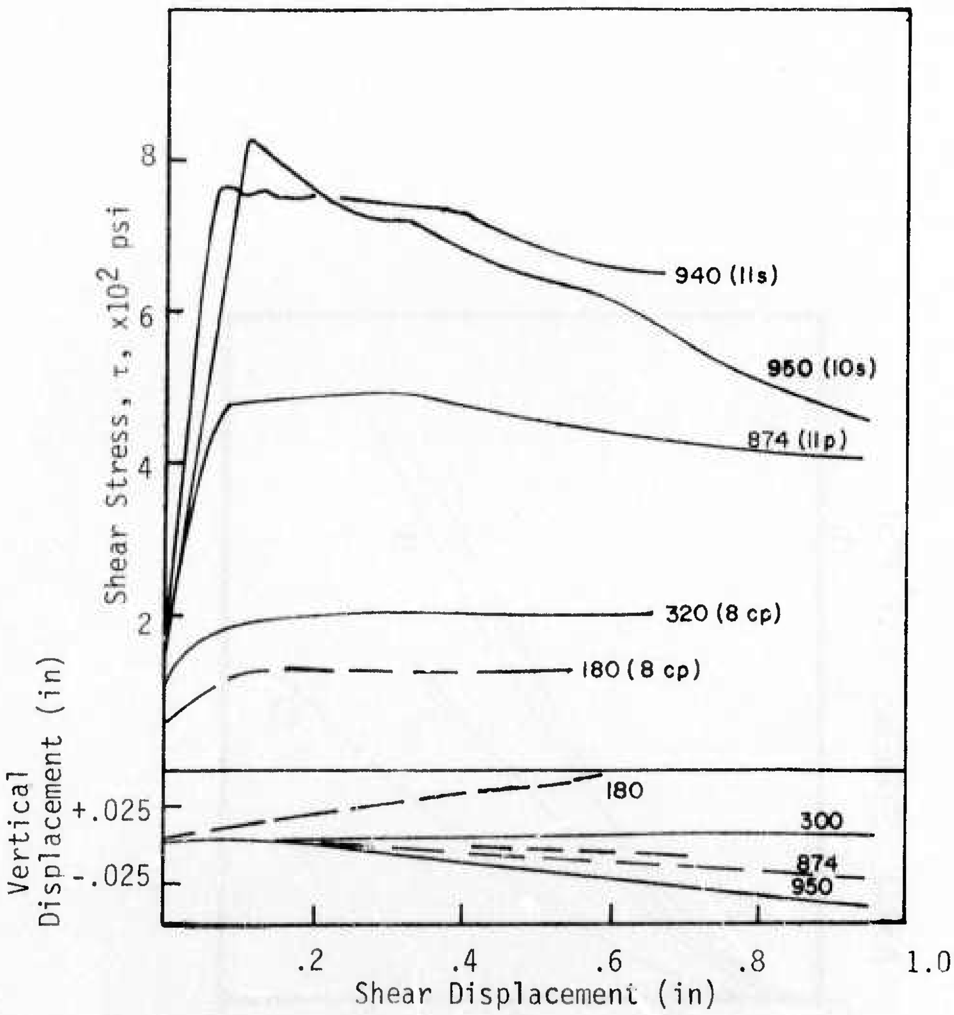


Figure 48. Frictional properties of several samples along a single joint.



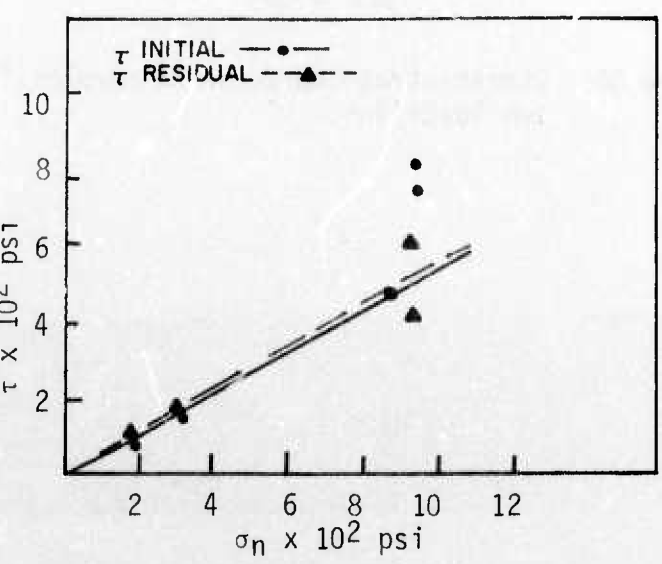


Figure 49. Frictional properties of several samples along a single joint.

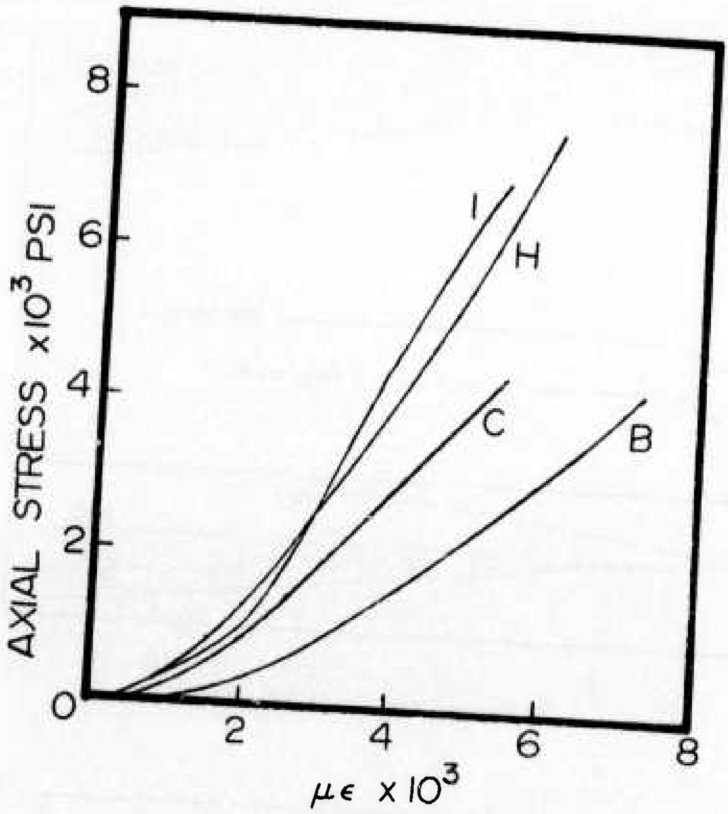


Figure 50. Stress-strain curve on NX samples from two loactions.

(Fig. 50). The specimens at this test site were significantly stronger (approximately 60%) than the quartz diorite tested in last year's program, which for this size has an average unconfined compressive strength of 4470 psi.

SECTION VII

DISCUSSION

Coefficient of Friction

Initial coefficients of friction (μ_i) of the three surfaces tested in the laboratory differed in their trends with increasing normal stress. The initial coefficient of friction of natural joints increased slightly with increasing σ_n (Fig. 51) while μ_i of the two artificial surfaces decreased. The μ_i of Brazilian surfaces decreased significantly with increasing σ_n (Fig. 52) while μ_i of the sawcuts was almost constant with respect to σ_n. These trends are similar to those seen by Coulson (Ref. 2) for artificial surfaces at lower normal stresses and smaller samples.

The difference in trend of μ_i with increased σ_n between the natural surfaces where μ_i increases slightly and the artificial surfaces where μ_i decreases with σ_n may be related to (1) the initial contact area which may be lower in natural joints than in the mated Brazilian and sawcut surfaces, and (2) the strength of the asperities. Logan (Ref. 10), on the other hand, found in triaxial tests that μ does not necessarily correlate directly with roughness but that it reached a minimum for a certain roughness and increased as the surface became either smoother or rougher.

Residual coefficients of friction (μ_r) for all three surfaces decreased with increasing normal stress with μ of Brazilian surfaces decreasing most significantly with increasing σ_n (Fig. 52). Linear least squares best fit curves to the data are shown in Figs. 51 and 52.

The coefficient of friction for most of the laboratory tests on natural joints increases then decreases with displacement. In other tests it increases to a maximum value then remains constant or increases slightly as a function

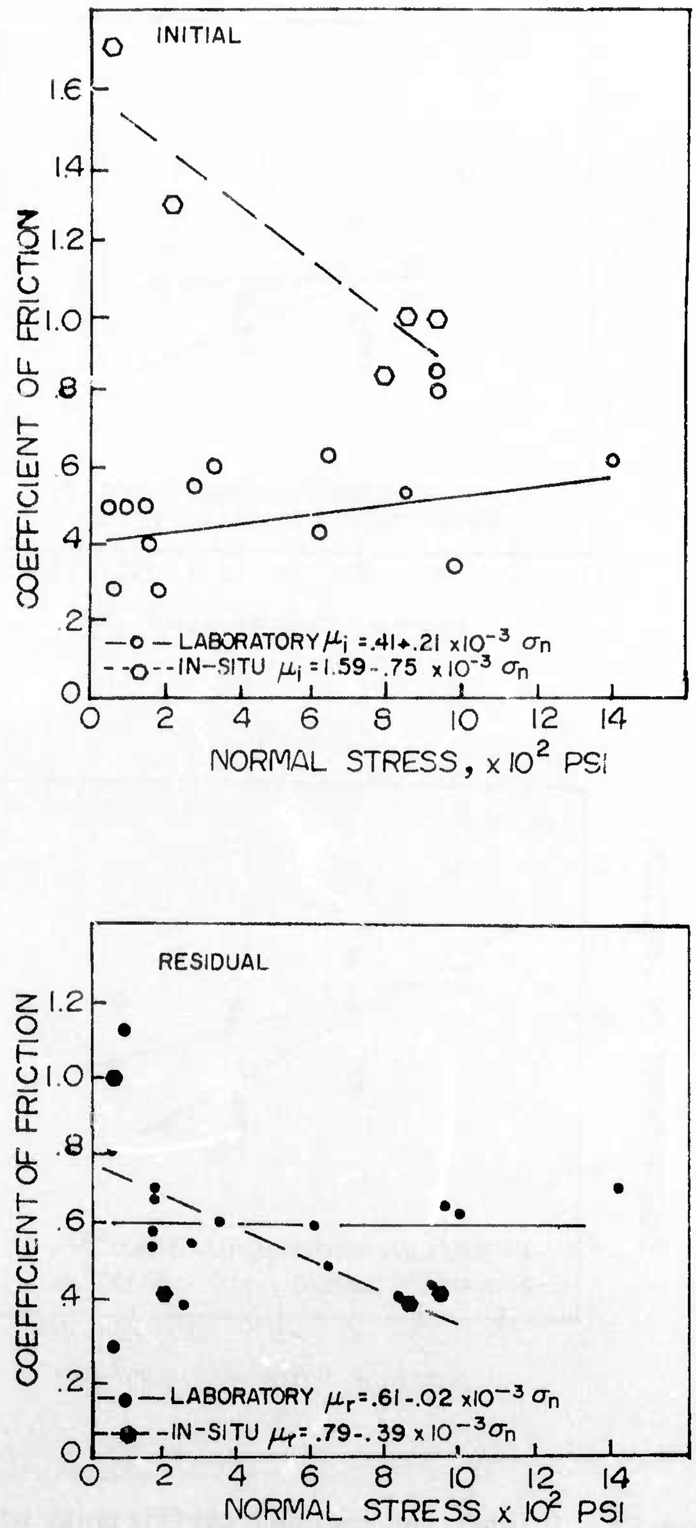


Figure 51. Initial and residual coefficients of friction of natural joints as a function of normal stress.

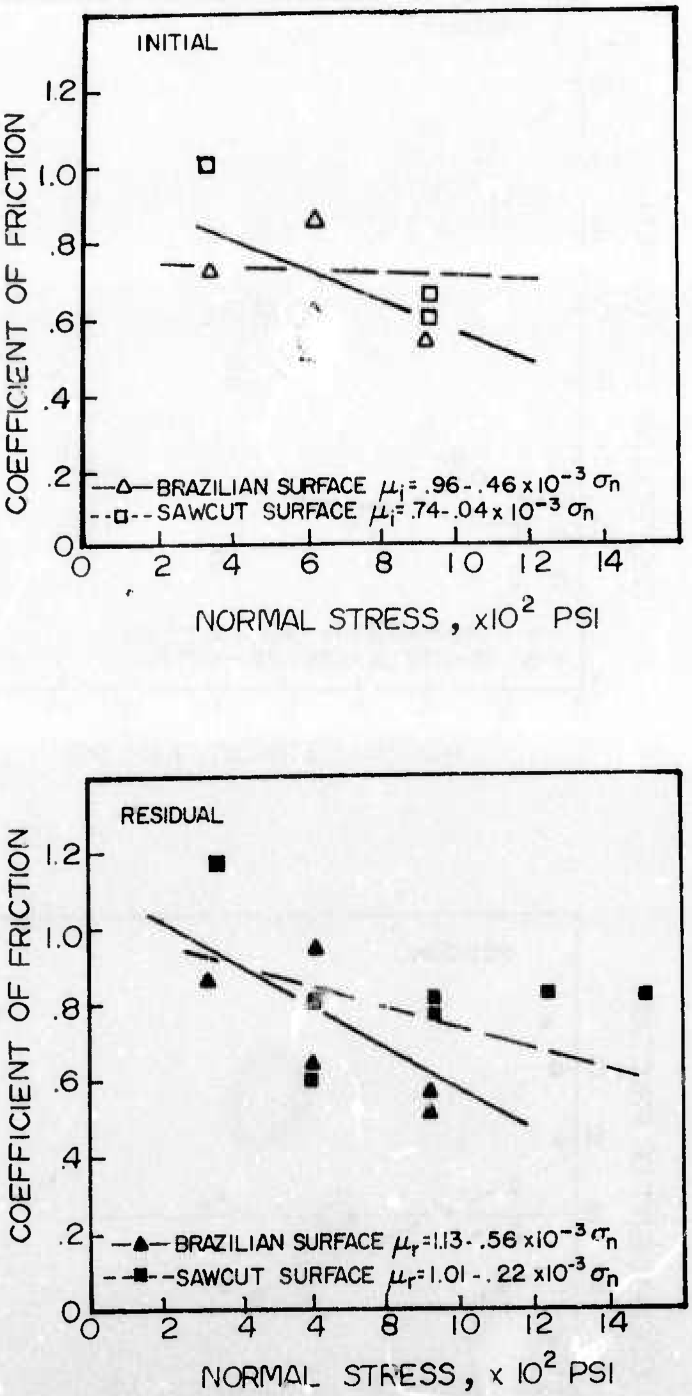


Figure 52. Initial and residual coefficients of friction of sawcut and Brazilian surfaces.

of displacement. Maximum values of μ_i are attained in the displacement range 0 - 0.15 inch. In a few tests at low σ_n (less than 180 psi), μ_i increased with displacement. Since most of our direct shear tests were servo-controlled to keep σ_n constant, a shear stress-displacement curve also represents a continuous plot of trends in coefficient of friction with displacement. For tests on artificial surfaces the trend in μ is the same; with μ increasing then decreasing slightly or remaining constant with displacement. These trends in μ as a function of displacement have been noted by Byerlee (Ref. 9) in triaxial tests on ground, mated, and virgin surfaces of small samples of Westerly granite at confining pressure to 87 ksi. On ground surfaces μ increased then decreased with displacement. For mated surfaces μ decreased with displacement. Displacements were much smaller so that residual shear stresses may not have been reached, but on the other hand the curves were flat at the displacements reached (<.25 inches) during laboratory tests.

Strength of the asperities also plays an important role in determining μ. Tests on Brazilian surfaces at comparable normal stresses gave a μ of .89 for rock with an unconfined compressive strength of 7.7 ksi but only μ of .54 for a specimen with a strength of 5.4 ksi indicating the shear strength of the asperities is correlative with strength of surfaces with comparable roughness.

Surface Area Effect

The effect of surface area on the shear strength of in-situ joints has not previously been studied systematically.

Usually a single or at most a few in-situ shear tests are conducted in conjunction with large construction projects. Several in-situ direct shear tests were conducted at the Auburn damsite in California (Refs. 5 and 11) but they were carried out on a variety of joints having different

orientations with respect to foliation, different roughnesses, and joint filling. All specimens also had a surface area of approximately 144 inches and displacement for individual tests was extremely small (0.04 inch). The average angle of friction obtained for the amphibolite was 44°. Laboratory studies on small samples over a range of areas from 0.32 to 1.97 cm^2 have been conducted by Byerlee (Ref. 17) who found no surface area effect. Our field tests covered a range in surface area from 22 to 795 square inches. All specimens in this series had a single vertical joint oriented at 45° to axis of loading. Both initial and residual shear strengths decreased with increasing surface area (Fig. 25). The shear strengths appeared to asymtotically approach a constant shear strength value at areas greater than 350 square inches. The decrease in initial shear strength is greater than the decrease in the residual shear strength. The initial and residual shear strength curves tend to parallel each other at areas greater than 200 square inches.

Differences between slopes of τ_i and τ_r curves may reflect the real variation in joint characteristics between the in-situ samples. Initial shear stress-displacement would take into account all initial characteristics while the τ_r curves may have normalized this difference (such as contact area, etc.) because of the displacement that has occurred. Residual values, therefore, more likely represent the true surface area effect. Because the size effect study was conducted on more than one joint (4), all located within a 100 foot radius, we cannot be positive that initial joint conditions were the same for all specimens tested. This, of course, is a problem inherent with practically all in-situ field test programs. Because of this and the relatively few number of tests (7) more work is needed in studying this areal effect.

The surface area effect is probably related to a roughness-contact area

relationship. Patton (Ref. 1) and Rengers (Ref. 6) have discussed the fact that there are asperities of at least three orders of size in natural joints ranging from hundredths of an inch to those on the scale of a foot or so. A trace of the intersection of the natural joint surface with the ground surface was made for all in-situ tests. Results indicate that a wave length of 3 - 12 inches was prevalent for the joints tested in the field. Contact area for these specimens was probably on the order of 10 - 15% as indicated by a post-test estimate of the disturbed contact area. It is still not fully clear how the joint characteristics interact to produce a resultant frictional property. Certainly joint roughness, contact area, strength of host rock and filling material all are involved in a rather complex manner. It was impossible to observe the post test surface area of the large samples because the weight of the specimen precluded excavation with available equipment.

For small surface areas one would also expect a continued increase in shear strength with decreasing surface area until a critical size-roughness-contact area requirement is met beyond which the shear strength would be constant. That may well be the case for the work of Byerlee who saw no surface area effect.

Stick Slip

Stick slip phenomenon was noted at high normal stresses but not at low normal stresses where stable sliding was noted in most of the tests run (Fig. 53). Byerlee (Ref. 9) noted stick slip in triaxial tests at only high confining pressures. Coulson (Ref. 2) also noted stick slip over a wide range of low normal stresses and rock types tested in direct shear.

Hoskins and others (Ref. 3) also noted stick slip during double shear experiments only on extremely smooth surfaces (35 μ inches) but not on

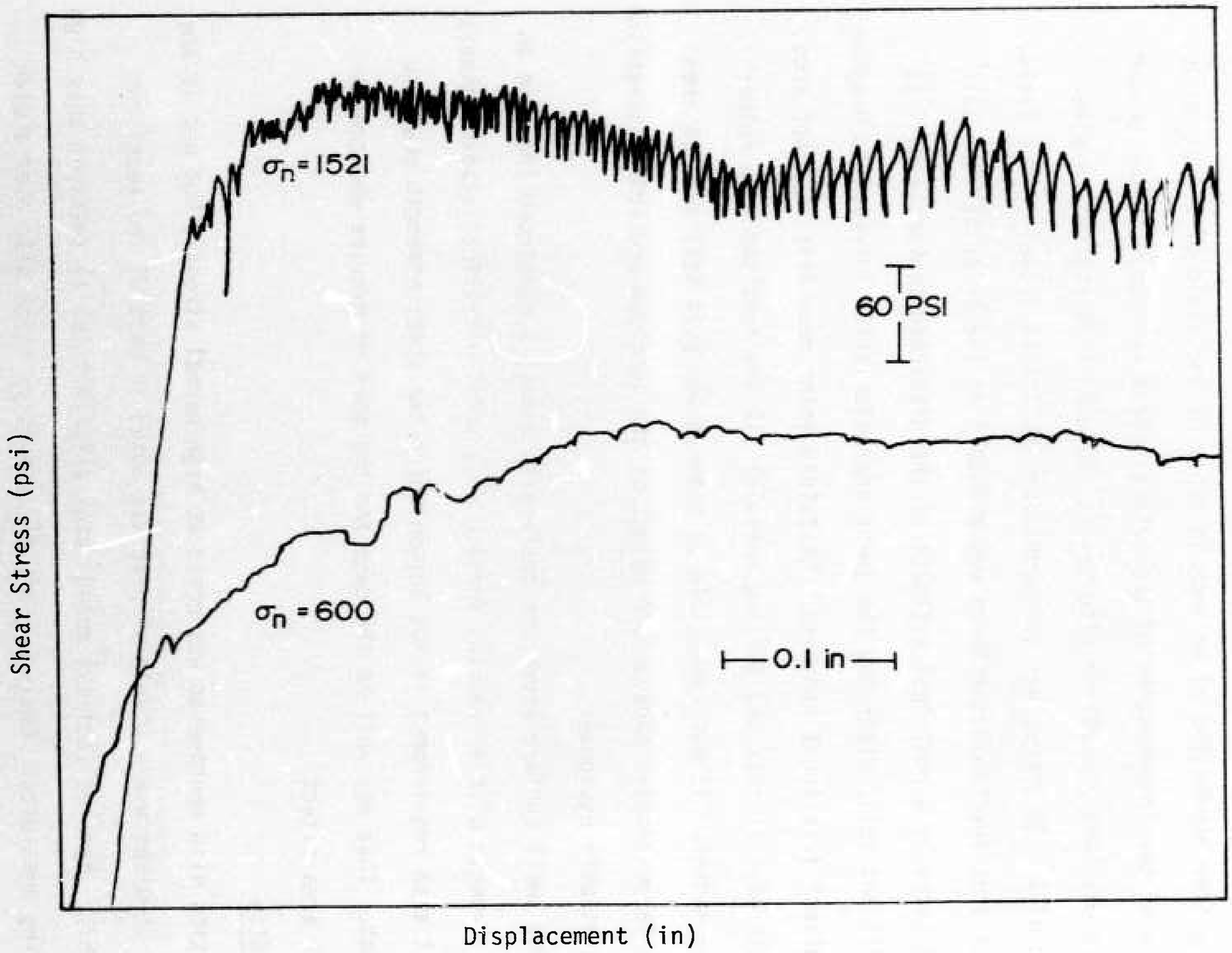


Figure 53. Stick slip phenomenon at higher normal stresses. Specimen size 6x6 inches.

rougher surfaces (>200 μ inches) where stable sliding prevailed. They do not feel that stick slip oscillations will be important in rock mechanics applications unless the surface is extremely smooth, not likely the case for in-situ joint surfaces.

Failure Criterion

Failure envelopes for jointed rock either in-situ or in the laboratory will reflect the characteristics of the joint surface such as roughness, including size and strength of asperities, type of filling material, and the characteristics of the loading system. The linear envelope dictated by the Coulomb-Navier friction criteria does not take into account the geometric component of shear strength resulting from size and shape of asperities on the surface. The geometric component leads to a greater friction angle for a given normal stress condition. The modified friction criteria $\sigma_n = c + \tan(\phi + i)$ still results in a linear relationship for the coefficient of friction (Patton, Ref. 1). Patton also indicates that the failure envelope is curved at least at low normal stresses (less than 100 psi) due to multiple modes of failure resulting in a changing $(\phi + i)$ value.

This geometric effect (i) is also a function of the normal stress, decreasing with increasing normal stress. This is obvious because the dilation of the joint also decreases with normal stress and in fact compresses at higher normal loads (Figs. 34, 40 and 42).

It now seems clear that the frictional sliding is more complicated than previously realized. A comparison of the failure envelopes for sawcut, Brazilian and natural joint surfaces indicates that the geometric effect is present in the 2° difference in ϕ between rougher Brazilian surface and the smoother sawcut. The sawcut may still be rough enough (700 μ inches) to also have a geometric component of its own. The natural joints, on the

other hand, have a lower ϕ value than either of the two other smoother surfaces. The counteracting influence is undoubtedly due to (1) lower contact area of the natural joint in contrast to the mated artificial surface. Of course, for sliding friction experiments in which the surface is repeatedly loaded and sheared the contact area increases as large slickensides and gouge develop with increasing normal loads; (2) the presence in some cases of joint filling materials; and (3) weathering of the natural joint surface by water thereby decreasing the strength of the asperities in contrast to the fresh nature of the artificially prepared specimens.

Dilation

Dilation of the joint during the shearing process has been observed at low normal stresses and has been attributed to the "riding up and over" of the asperities as they move past one another. In our field tests, linear potentiometers located at three positions along the joint (Fig. 17) were used to monitor dilation. Usually no displacement occurred across the joint during initial loading until shear displacement commenced. In one case slight compression of the joint occurred during initial loading (Fig. 30). In most cases as shearing began the joint dilated to different degrees depending on instrumentation location with respect to the wave length and amplitude of the undulation in the joint surface (Figs. 27, 29 and 30). In some cases the joint dilated then closed during the shearing process (Fig. 27). In the laboratory tests DCDTs on both sides of the specimen monitored vertical displacement during the shearing process. Dilation was found to be a function of the normal stress for all surfaces tested. At low normal stress the joint dilates with shear displacement but dilation decreases with increasing normal stress. Sawcut surfaces (Fig. 41) tested at a normal load of 300 psi dilated; those at 600 psi showed no vertical

movement; and those at 900 psi compressed. Brazilian surfaces (Fig. 42) at σ_n = 300 psi dilated during displacement while surfaces at σ_n = 600 psi dilated for displacement up to 0.3 inch then compressed. Tests at 900 psi simply compressed. Vertical displacements exhibited by natural joints were more variable (Figs. 39, 40 and 49). They tended to dilate to normal stresses up to 300 psi but compressed upon shear displacement at higher normal stress. The magnitude of joint compression tended to increase with both normal load and displacement. At these higher normal stresses the asperities are undoubtedly sheared off and the geometric effect is small or negligible.

Comparison of Jointed and Unjointed Rock

To fully describe the behavior of the in-situ rock mass structural discontinuities (joints, faults, foliation planes and bedding planes) must be taken into account. The question arises, how much do these discontinuities modify the behavior of the rock mass and can one estimate deformational (including frictional) mass properties of rock from laboratory tests on small rock specimens? To compare properties of jointed and unjointed specimens the unconfined compressive strength of solid NX size cores from the current test site is compared with those from a former test site located two miles to the south (Fig. 1). The average compression at the current site where most of the in-situ tests were run was 7.3 ksi as compared to an average of 4.5 ksi at the other site in the quartz diorite; a ratio of 1.65. Strengths of the former site were adjusted higher by a factor of 1.65. Adjusted strengths and moduli (Fig. 54) indicate that specimens containing joints which have not displaced do not have lower strengths or moduli than unjointed specimens of equal size. Modulus data for all specimens is scattered and does not seem to vary with specimen size. Strength data indicates a significant decrease in strength with increasing size. Specimens containing joints

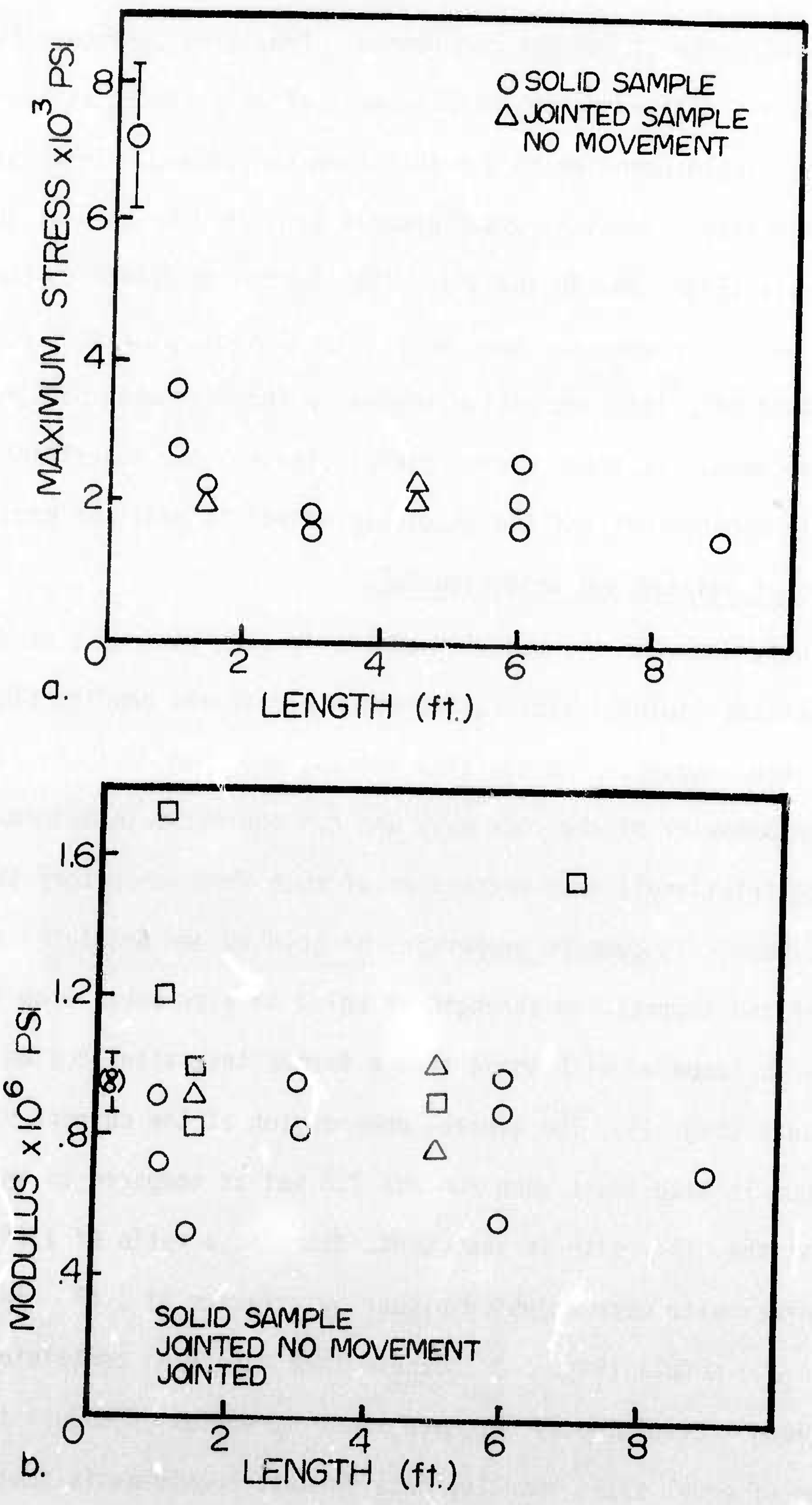


Figure 54. Normalized strength (a) and modulus (b) of jointed and unjointed diorite as a function of specimen length.

oriented favorably with respect to sliding have lower strengths and these strengths are directly related to the joint orientation. Strengths increase as the angle between the axis of loading and the joint increases from 30° to 52° (Fig. 55). Beyond 52° the joints did not move. Multiple jointed specimen displacement along those joints oriented most unfavorably with respect to the normal load. In the case of one sample with two joints oriented 45° to axis of loading (Fig. 7) a calcite coated joint displaced before a joint without a filling material indicating composition and thickness of this material is another important parameter in determining frictional properties.

Comparison of Field and Laboratory Data

Results from field and laboratory tests should be analyzed at comparable normal stresses and scaled according to the relative surface area. In-situ tests were conducted over a range of surface areas from 22 to 1123 square inches. Because the angle between the joint and axial load was predetermined, over the range 30-60°, the initial coefficient of friction was also predetermined, although the magnitude of shear and normal stresses was not. Residual coefficients of friction were not predetermined. Laboratory tests were conducted on natural joint surfaces having a surface area of approximately 36 square inches. In laboratory tests the normal stress was predetermined and the specimen subsequently sheared. The magnitude of the shear strength and thus the initial and residual coefficients of friction were therefore unknown. Therefore, the geometry and loading conditions are different in the in-situ and laboratory tests. For laboratory tests to accurately simulate in-situ loading conditions, proportional loading tests where the ratio of τ/σ_n is fixed by servo-controlling will have to be run. This is planned for the future. If possible, correlation should also be made between specimens tested in-situ or cored from the same joint (Fig. 5). This was not possible in all cases.

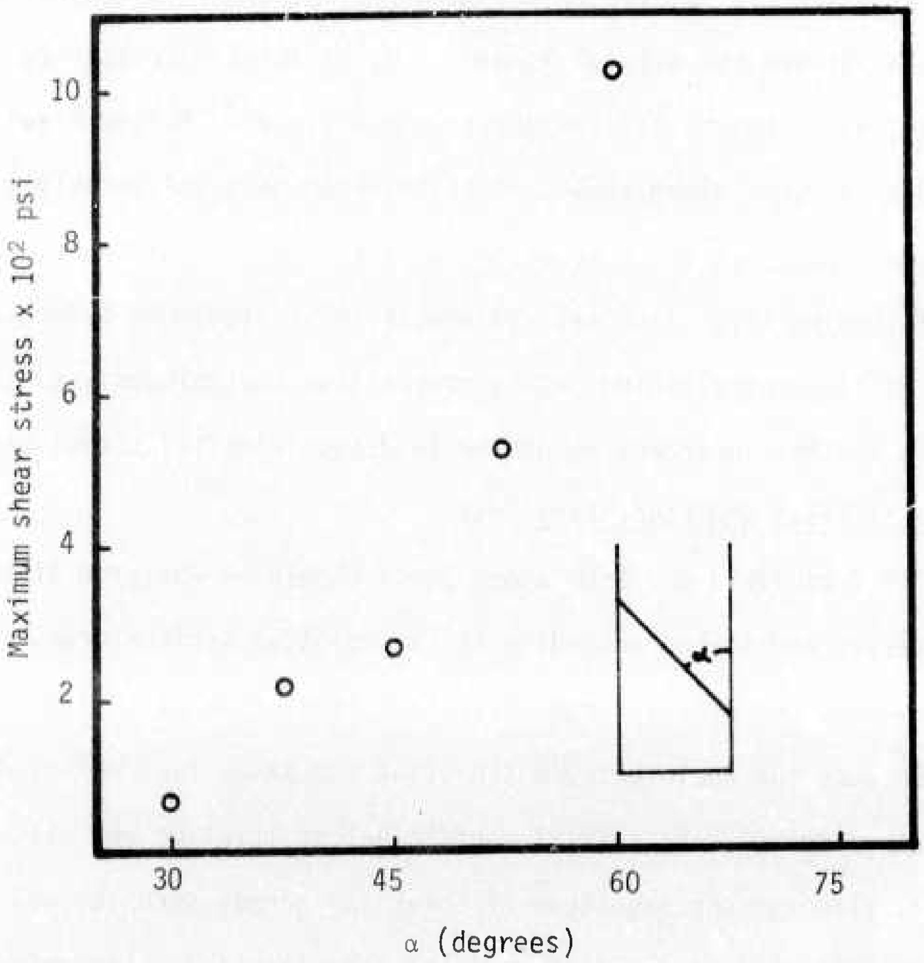


Figure 55. Initial shear strength as a function of the angle between the joint and axis of loading.

Initial coefficients of friction (μ_i) of the in-situ tests decreased with normal stress while laboratory tests increased slightly with σ_n. Residual coefficients of friction (μ_r) of both field and laboratory decreased with σ_n, but in-situ tests decreased more significantly than the laboratory tests (Fig. 51). Residual coefficients of friction of the in-situ tests agree reasonably well with μ_r from laboratory tests.

Results from in-situ field experiments (α=45°) and laboratory tests indicate that at higher normal stresses (850 psi and greater) the initial shear stress for field tests are slightly higher than for laboratory tests of comparable size and initial stresses are reached at less displacement than for laboratory tests. Initial and residual shear strengths are plotted for laboratory specimens 11s and 10s which have coefficients of friction comparable to the in-situ tests (Fig. 25). Both τ_i and τ_r agree reasonably well with the field data for comparable surface areas. In general, however, residual shear strengths of in-situ tests are lower than laboratory tests for comparable normal stresses. The residual friction angle for in-situ tests is 30° compared to 34° for natural joints tested in the laboratory (Fig. 56). Differences in initial shear strengths between field and laboratory specimens may be due to (1) joints being bridged in large in-situ tests, (2) the relative "softness" of the field test system compared to the servo-controlled laboratory system, and (3) the joints in the laboratory specimens being disturbed during coring or subsequent preparation.

More study is needed in comparing field and laboratory data before detailed correlation can be made and scaling concepts rigorously developed. This study is a step in that direction.

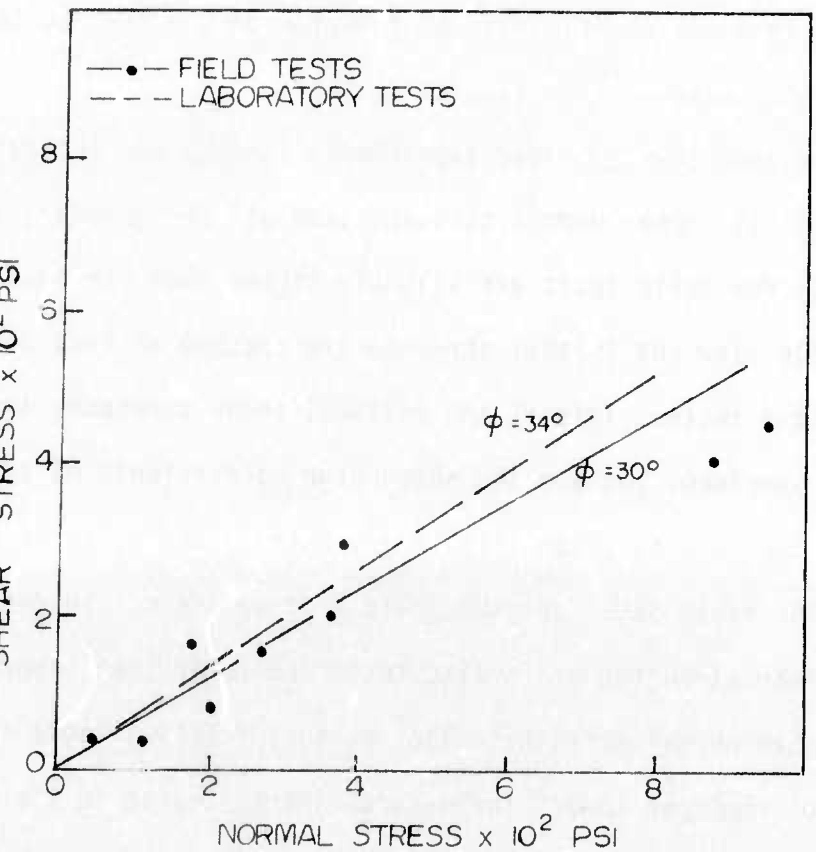


Figure 56. Comparison of residual friction envelopes for field and laboratory tests.

SECTION VIII

CONCLUSIONS

1. The experimental technique developed for determining frictional and deformational properties of in-situ jointed specimens has proven feasible and allows for testing of large surface areas.

2. Both initial and residual shear strengths of in-situ jointed quartz diorite specimens decreased with increasing surface area over a range of surface areas from 22 to 795 square inches. This decrease is thought to be related to a surface roughness-contact area relationship exhibited by natural joints. Residual shear strengths are relatively constant for areas greater than approximately 350 square inches. Both initial and residual coefficients of friction decreased with both normal stress and displacement.

3. In laboratory tests the initial coefficient of friction of natural joints increased slightly with normal stress while residual coefficient decreased slightly with increased normal stress. For artificial surfaces both μ_i and μ_r decreased with normal stress.

The change in coefficient of friction with displacement seems to be complicated for natural joints although in most tests μ increased then decreased with displacement; in many tests, however, μ remained constant. For both types of artificial surfaces μ decreased with displacement.

4. The friction angle includes not only a geometric effect but is also a function of contact area and strength of asperities. Rougher surfaces have a higher friction angle than smoother surfaces but a rougher surface, like a natural joint, can have a lower friction angle than a smoother but perfectly mated surface because of the lower contact area. The shear strength of comparable natural joints is a function of the mineralogy and thickness of

the filling material in the joint and may overshadow normal stress and area effects.

5. In field tests the dilation of the joints is a function of the wave length and amplitude of the joint. In laboratory tests both natural and artificial joints dilate during the shearing process at low normal stress (less than 300 - 600 psi) but did not dilate at higher normal stresses (600 - 1500 psi). This seems reasonable because the asperities are ridden up and over at low normal stresses. The magnitude of both dilation and compression increases with increasing shear displacement.

6. In the specimens tested, the strengths and modulii of jointed specimens prior to shearing and unjointed specimens are similar. However, if the joint filling material is thick enough so that adjacent joint surfaces are not in contact or if the joint is significantly open the initial modulus would be that of the filling material until the sides of the joint mate. Depending on joint geometry and the magnitude of the normal load, the frictional properties could be determined by the properties of the filling material rather than those of the host rock as exemplified by the tests with calcite filled joints.

7. The shear strength of a in-situ jointed specimen, all other things being equal, is a function of the geometric relationship between orientation of the joint to the principal load. The shear strength of the specimen increases significantly as the angle between the joint and load increased from 30° to 52°. At angles of 60° and greater the joint did not shear and the specimen failed at its unconfined compressive strength. In multiply jointed samples the strength was controlled by the joint oriented most unfavorably with respect to the load. Other joints in the specimen sheared only after displacement was completed along this unfavorable joint and the

joint became locked against an adjacent block.

8. Development of a servo-controlled direct shear apparatus makes it possible for the first time to monitor and program normal load-displacement conditions to account for changes in load and contact area during shear displacement. Proportional loading tests, where the relationship between shear and normal load can be held at any predetermined ratio can also be run.

9. A combination of field and laboratory tests is required to adequately describe the frictional and deformational properties of a rock mass. Selected field tests are needed to establish scaling curves so that additional laboratory tests on natural joints can be used effectively. Data from laboratory tests is certainly much easier and less costly to obtain than field data. Both in-situ and laboratory tests must be conducted under conditions simulating the field environment. The stress range at which the rock and/or joint(s) should be tested will be a function of the magnitude and direction of the load on the rock mass and the geometry of the joint system with respect to the direction of loading.

10. Residual values of shear stress and coefficient of friction are probably more indicative of rock mass frictional properties and should be used in scaling from small areas to surface areas of interest. This area of interest is determined by the spacing, continuity, geometry of the in-situ joint system. Initial value data tend to scatter widely for natural joints because of localized asperities, the discontinuous nature of joint filling material and variable degree of joint healing.

11. Although it seems possible to correlate field and laboratory data by use of scaling to account for size effects, more work is needed to compare field and laboratory data to see if scaling applies to other rock and joint types and deformational properties. When scaling from laboratory to field

tests not only size but characteristics such as total contact area, wave length and amplitude of the different sets of asperities along the natural joint must also be taken into account. This assumes that the joint surface strengths and the type and amounts of joint filling materials will be similar in the in-situ and laboratory specimens.

ACKNOWLEDGEMENTS

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13. ABSTRACT

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A field and laboratory program was conducted to determine the frictional and deformational properties of Cedar City quartz diorite. In-situ tests on joint surfaces ranging in area from 22 to 795 square inches indicate a decrease in initial and residual shear strengths with increasing area. Laboratory data should be scaled appropriately depending on joint size, wave length and amplitude as compared to in-situ joints. Strength and modulus of jointed and unjointed specimens are similar until shearing begins when the strength of joint samples decreases. Field tests on specimens with single and multiple joints oriented at different angles to the axial stress indicate a significant geometric effect and that unfavorably oriented joints determine the shear strength of the entire joint block until that joint interacts with adjacent blocks. Servo-controlled direct shear laboratory tests on natural and artificially prepared joints over a normal stress range of 60 to 1500 psi indicate that there is a geometric effect with roughness but that this may be overridden by a contact area and/or asperity strength effect present in natural joints. This gives rise to lower friction angle than in smoother but perfectly mated artificial surfaces. Initial and residual coefficients of friction are a function of both normal stress and displacement. Dilation of both natural and artificial joints occurred during shearing at lower normal stress (<300 psi) but the joints compressed at higher normal loads. Dilation that occurred in field tests was related to the wave length and amplitude of the joint. Stick slip phenomena was noted in some of the laboratory tests at high normal stresses but not at low stresses or in any of the in-situ tests.

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